A Synthesis of Post-Fire Road Treatments for BAER Teams: Methods, Treatment Effectiveness, and Decision-Making Tools for Rehabilitation

Final Report to the Joint Fire Sciences Program

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Abstract

A synthesis of post-fire road treatment information was compiled to assist BAER specialists when making road rehabilitation decisions. A questionnaire was developed; 30 interviews of BAER team engineers and hydrologists were conducted; grey literature and other relevant publications were acquired and analyzed; and road rehabilitation procedures and analysis tools were reviewed. Post-fire road treatments are implemented if the values at risk warrant the treatment, and are based on regional characteristics, including timing of first damaging storm and window of implementation. Post-fire peak flow estimation is important to select road treatments. Interview results indicate that USGS methods are used for larger watersheds (> 5 mi^2); and NRCS Curve Number methods are used for smaller watersheds (< 5 mi^2). These methods are not parameterized and validated for post-fire conditions. Many BAER team members used their own rules to determine parameter values for USGS regression and NRCS CN methods; therefore, there is no consistent way to estimate post-fire peak flow. Many BAER road treatments for individual stream crossings were prescribed based on road/culvert surveys, without considering capacities of existing road structure and increased post-fire peak flow. For all regions rolling dips/water bars, culvert upgrading, and ditch cleaning/armoring are the most frequently used road treatments for overall Regions. For Forest Service Regions 1 and 4, culvert upgrading is preferred, especially for fish-bearing streams. For Forest Service Region 3, culvert removal with temporary road closure and warning signs is preferred. Except for culverts, insufficient data is available on other road treatments to estimate their capacity and to evaluate their effectiveness.

The objectives of the study and how they were met are described below.

Objective	Comments
1. Develop a questionnaire for acquiring qualitative and quantitative information on post-fire road rehabilitation.	The questionnaires are detailed in Appendix A.
2. Conduct interviews of BAER team engineers and hydrologists to define specific needs of BAER specialists with respect to post-fire road rehabilitation.	Thirty BAER team members in six Regions were interviewed. Details are presented in table 1.
3. Analyze gray literature and conduct additional literature review of relevant publications based on needs identified from interview results	Appendix B is an annotated bibliography of the results of the gray literature from the interviews.
4. Review and synthesize road rehabilitation procedures and analysis tools that would be most useful to BAER teams. Specific tools of interest include those which estimate post-fire runoff and sediment flows and road structure capacities.	Chapter 3 contains this review and synthesis.
5. Design easily navigable post-fire road guide for BAER teams to access during rehabilitation responses. This will include both electronic and hard copy resources.	Located at RMRS-Moscow web site http://forest.moscowfsl.wsu.edu/BAERTOOLS/

6. Transfer information on new resource through workshops and presentations to agencies involved in post-fire road rehabilitation.	Announced completion of the study at the Regional BAER Coordinators Monthly Meeting in October 2008. Made two other progress reports at National and Regional BAER coordinator meetings.

Keywords: wildfire, BEAR, burned area, emergency response, peak flow, roads, drainage, treatment

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1. Introduction

Wildland fires can cause extreme changes in the landscape which can drastically influence surface runoff and sediment transportation. Removal of the forest duff layer causes increased runoff and subsequent increases in peak flow and sediment transport. These increased flows can impact forest resources and infrastructures. Roads are one of the most-impacted forest infrastructures. In addition to facilitating transportation of vehicles, roads are designed to manage water to desired locations and prevent wash outs. Post-fire flows often exceed design capacity, requiring that many structures be treated following fires; e.g., culverts sized for unburned forest conditions are often unable to pass the new, higher flows and are replaced with larger ones. Nationwide road structure replacement costs in the 1990's were about 20 percent of the total post-fire rehabilitation expense (Robichaud and others, 2000).

1.1 Problem Statement

Watersheds with satisfactory hydrologic conditions (greater than 75% of the ground covered with vegetation and litter), and adequate rainfall, sustain stream baseflow conditions for much or all of the year and produce little sediment and erosion. Fire consumes accumulated forest floor material and vegetation, altering infiltration by exposing soils to raindrop impact or creating water repellent soil conditions, and reducing soil moisture content. Runoff plot studies show that, when severe fire produces hydrologic conditions that are poor (less than 10% of the ground surface covered with plants and litter), surface runoff can increase more than 70% and erosion can increase by three orders of magnitude (DeBano and others, 1998; Robichaud, 2005).

In the post-fire environment road drainage features must accommodate flows under these changed and variable conditions to prevent failure. Road structures designed for the unburned forest condition are often unable to accommodate increased runoff, sediment, and debris following fire. BAER teams estimate post-fire increases in stream flows and make judgments on the ability of existing road structures to accommodate these new flow regimes. If necessary, treatments are prescribed to protect the safety of users and the road infrastructure investment, as well as to prevent disruption of use, or to prevent unacceptable degradation of critical natural and cultural resources.

BAER team members use a variety of tools to estimate the post-fire increase in runoff and sediment. These vary from local expertise to computer models. This synthesis of commonly used post-fire assessment tools and road treatments will aid BAER team members in responding to the tight time frames allotted for rehabilitation decisions.

1.2 Study Objectives

The overall goal was to develop a resource for BAER teams to assist in making post-fire road rehabilitation decisions. We synthesized the most useful post-fire analysis tools for use in determining the required capacity of road structures and guidelines and procedures for prescribing road treatments after wildfire. Our specific objectives were to: (1)

develop a questionnaire for acquiring qualitative and quantitative information on post-fire road rehabilitation; (2) conduct interviews of BAER team engineers and hydrologists to define specific needs of BAER specialists with respect to post-fire road rehabilitation; (3) analyze gray literature and conduct additional literature review of relevant publications based on needs identified from interview results; (4) review and synthesize road rehabilitation procedures and analysis tools that would be most useful to BAER teams; specific tools of interest include those which estimate post-fire runoff and sediment flows and road structure capacities; (5) design an easily navigable post-fire road guide to access during rehabilitation responses; this included both on-line and hard copy resources; and (6) transfer information through workshops and presentations to agencies involved in post-fire road rehabilitation. This report summarizes our accomplishment of the study objectives.

2. Methods

This study includes USDA Forest Service BAER projects in the Western continental U.S. (Regions 1 through 6). We began by requesting Burned Area Report (FS-2500-8) forms and monitoring reports from the Regional headquarters and Forest Supervisors' offices. 1) We developed interview questionnaires and 2) interviewed BAER specialists, regarding their experiences with post-fire rehabilitation. 3) We analyzed gray and peer-reviewed literature acquired from the interviews and literature search. 4) Then we reviewed and synthesized quantitative and qualitative information on procedures for prescribing road treatments after wildfire, estimation of post-fire runoff and sediment, and the road treatments.

2.1 Burned Area Report Data

The USDA Forest Service Burned Area Report form contains the fire name, watershed location, size, suppression cost, vegetation, soils, geology, lengths of stream channels, roads, and trails affected by the fire. The watershed description includes areas in low, moderate, and high burn severity categories and the area of water repellent soil. Erosion hazard rating and estimates of erosion potential and sediment potential are included. Additionally, hydrologic design factors are included, such as estimated vegetation recovery, design chance of success, design storm recurrence interval, storm duration, storm magnitude, design flow, reduction in infiltration, and post-fire runoff flow. Values at risk are described and the probability of success for hillslope, channel, and road treatments are estimated. Cost estimates of no action (loss) versus cost of selected alternatives are identified, as well as BAER funds requested and other matching funds.

2.2 Interview Survey

Interview forms (Appendix A) were developed after modification of the survey form from a previous study (Robichaud and others, 2000). The forms were used to record information during interviews with BAER team members. Questions were designed to elicit opinions regarding the interviewees' experience with treatments used on their forests and other fires they had worked on. The interview survey was composed of three parts (1) hydrologic design factor questions of Burned Area reports, i.e., how they estimated post-fire runoff and sediment; (2) road treatment questions, i.e., frequent-used road treatments; and (3) aftermath road treatment questions, i.e., success and failure of the prescribed treatments. Prior to conducting interviews, information such as Burned Area Report forms and post-fire monitoring reports were requested to familiarize the interviewer with the various fires and treatment used. Onsite interviews were conducted because much of the supporting data were located in the interviewee's offices and could be retrieved during the interviews. Attempts were made to ask questions that would allow for ranking results, because much of the information was qualitative.

2.3 Analysis Methods

Interview survey results were analyzed using Microsoft Excel™. Ranked information results were given a value from one to three with the first ranking receiving three points; second two points; and third one point. Runoff, peak flow, and sediment yield estimation methods used by BAER teams were evaluated; their benefits/drawbacks were described, based on the comments of BAER interviewees, scientific literature, and the judgment of the proposal's PI and Co-PI as suggested by the JFSP. Examples of the different estimation methods from BAER reports were provided. Qualitative answers and comments were grouped to draw meaningful inferences.

3. Results and Discussion

3.1 Overview of Data Collected

Collected data were categorized into the following (1) burned area report (FS 2500-8), acquired from Regional BAER coordinators, (2) published literature from literature review/search, (3) interview results from BAER specialists, and (4) gray literature and unpublished data from interviewed BAER specialists. The published literature can be found in the references. The list of gray literature and unpublished data can be found in Appendix B.

3.2 Interview Survey

A total of 30 BAER specialists were interviewed in this study. We visited a total of 28 BAER specialists' office to conduct interviews face-to-face, and also acquire any gray literature and monitoring reports while interviewing them. Two BAER specialists were interviewed by phone, due to schedule conflicts. Interviewed BAER specialists were mostly hydrologists (45 %), engineers (22 %), and soil scientists (20 %) (table 1); therefore, we have a representative sample of specialists involved in post-fire runoff and sediment estimation methods, as well as road treatment selection. The experience of the interviewed BAER specialists range from 6 to over 30 years.

[Table 1. Background of interviewed BAER specialists by Regions]

3.2.1 Hydrologic Design Factor

The Burned Area Report contains a section titled "Hydrologic Design Factors" containing a series of factors used to estimate the need for post-fire treatments. The following section summarizes the interviewee's methodology to complete this section. For each of the factors we will discuss the most popular methods that comprise 80 % of the responses. All responses are listed each table.

For **estimated vegetation recovery period**, most of interviewed BAER specialists used "professional judgment" (42 %) or consulted with local botanists, ecologists, soil scientists, or hydrologists (40 %) (table 2). It was unclear what method the consulted specialists used. Research results (18 %) and "2 to 3 years" (8 %) were the next popular responses.

[Table 2. Estimated vegetation recovery period used by BAER specialists]

For **design chance of success**, most BAER specialists (78 %) used professional judgment (table 3). The interviewed BAER specialists without hydrology or engineering backgrounds consulted with hydrologists (13 %). It was unclear what method the consulted hydrologists used.

[Table 3. Design chance of success used by BAER specialists]

For **equivalent design recurrence interval**, there was no clear preference with the most frequent answer being "consult w/ hydrologist" (36%). It was unclear what method the consulted hydrologist used. Fixed values of 10 years (14%) and 25 years (14%) were the next most common reply (table 4).

[Table 4. Equivalent design recurrence interval used by BAER specialists]

For **design storm duration**, there was no clear preference with the most frequent answer being "consult w/ hydrologist" (44%). It was unclear what method the consulted hydrologist used. One hour duration (17 %), various duration depending on damaging storm (13 %), and 30 minute (12 %) were the next most common reply (table 5). Damaging storm is further discussed in Chapter 3.3.2 *Damaging Storm*.

[Table 5. Design storm duration used by BAER specialists]

For **design storm magnitude**, a majority of the interviewees with an hydrology background used NOAA Atlas (46 %), and ones without an hydrology background consulted with hydrologists (40 %) (table 6). It was unclear what method the consulted hydrologist used. A small number of BAER specialists used other methods, such as Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly, 2007) and CLIGEN (USDA ARS and Forest Service, 2008). Also one interviewee specifically identified that, for watershed less than five square miles, the damaging storm is a 5 minute duration, 6 inches/hour intensity, convective storm in Region 2 and 3. In Colorado the damaging storm is a 2 year return period, 24 hour duration, 0.1 inch/hour intensity, convective storm in July or August.

[Table 6. Design storm magnitude used by BAER specialists]

Estimated reduction in infiltration was mostly estimated from soil burn severity (USDA Forest Service, 2007) maps (46 %) or measured in the field (29 %) (table 7).

[Table 7. Estimated reduction in infiltration used by BAER specialists]

To estimate **design flow** (pre-fire peak flow), most of interviewed BAER specialists used the USGS Regression (50 %), Curve Number (18 %), and consulted with hydrologist (18 %) (table 8). It was unclear what method the consulted hydrologist used. To estimate **adjusted design flow** (post-fire peak flow), most of interviewed BAER specialists used the USGS Regression (43 %), Curve Number (28 %), rule of thumb by Kuyumjian (personal communication, Kuyumjian, 2007; 7 %), and TR55 (USDA NRCSb, 2005; 7 %) (table 8). Detailed information about each method is discussed in Chapter 3.4 *Post-fire Runoff and Erosion Estimation*.

[Table 8. Pre- and post-fire peak flow estimation methods used by BAER specialists]

3.2.2 Road Treatment

The 2500-8 contains a section that describes the BAER team's road treatment recommendations The following section summarizes the interviewee's preferred road treatments.

Rolling dips/water bars/cross drain, culvert upgrading, ditch cleaning, armoring, culvert removal, trash racks constituted 80 % of the most frequently used road treatments. All responses are shown in table 9. Rolling dips/water bars/cross drain was used most frequently throughout the Regions. Culvert upgrading was used mainly in Region 1, 4, and 6 where fish habitat protection is relatively a high priority. Culvert removal was used often in Region 3 where flash flooding is common. Trash racks were used in Region 3 and 5, and culvert riser was only used in Region 5.

[Table 9. Frequently recommended road treatments by BAER specialists by Region]

To calculate the treatment cost, BAER specialists consulted with engineers, followed regional cost guides, and modified and used the cost of previous years. Often three percent yearly interest was applied to the cost of previous year. Some BAER specialists added 20−25 % emergency factor, and a 35 % overhead fee. Indefinite Delivery Indefinite Quantity (IDIQ) contracts were favored by some BAER specialists, which are a type of contract that provides for an indefinite quantity of supplies or services during a fixed period of time (Office of Federal Procurement Policy, 2008).

3.2.3 Road Treatment Effectiveness Monitoring

To evaluate the prescribed road treatments, monitoring reports and any follow up records are needed; however, most interviewed BAER specialists did not have monitoring reports or any follow up treatment information. A limited number of monitoring reports were acquired during the interviews. Most monitoring reports had pictures and a description of the BAER treatments; however, they did not provide enough information to evaluate road treatment effectiveness. Furthermore, effectiveness to National Forest Systems usually means "proper installation of prescribed treatments" instead of "performance of treatments against designed conditions".

3.3 Post-fire Road Rehabilitation Procedures

When prescribing post-fire rehabilitation treatments, most BAER specialists follow similar procedures. Many BAER interviewees highlighted important aspects of these BAER procedures. The most notable comment was that prescribing road treatments was different among Regions since climates are different. This local knowledge will help prescribing road treatments after wildfire as follows.

3.3.1 Values at Risk

BAER treatments are prescribed, prioritized, and implemented, depending on the values (i.e., life, safety, property) and/or resources (natural or cultural) which are at risk due to the burned condition of the forest. If there are no values or resources at risk, no BAER treatment is needed. A recent publication (Calkin and others, 2007) provides a reliable and repeatable method to access values at risk.

3.3.2 Damaging Storm

A damaging storm is the precipitation event that will likely threaten human lives, cause damage to property, or road structures within the burned-over watershed or downstream values. A damaging storm can be a convective storm, a summer thunderstorm, or a rain-on-snow event depending on the Region. The damaging storm is a rain-on-snow event during spring snowmelt for mid to high elevation areas; convective storms from May to September for the majority of other areas; and winter frontal storms for portions of Region 5 and 6.

Our interviews with the BAER team members indicated that while they had a clear understanding of what constituted a damaging storm, the term “design storm” was often used interchangeably with the term “damaging storm”. A design storm is a storm event associated with a specified return period and is used as the basis for the design of stormwater-management systems. Both terms appear to be useful in BAER work, but we suggest a clear distinction between the two terms.

3.3.3 Window of Implementation

The window of implementation should be carefully considered during the BAER assessment; i.e., how much time the BAER implementation team has before a damaging storm will most likely affect the burned watersheds. Therefore, the assessment team should determine the number of treatments that can be implemented, then prioritize the treatments based on values at risk. This is especially important for the southwestern United States, where fire season is usually from May to July, and convective storms follow shortly. Ideally the BAER treatments would be implemented within 3 to 4 weeks. Any administrative help to speed-up the BAER implementation is useful such as the following

- Pre-ordering and stockpiling the necessary materials (such as warning signs).

- Contracting implementation equipment and associated personnel using Indefinite Delivery/Indefinite Quantity (IDIQ) contracts, and
- Close communication between assessment and implementation teams.

3.3.4 Probability of Success

The probability of treatment success is closely related to the values at risk. If the values at risk are high, high probability of success should be considered. The BAER treatment choice is determined by post-fire runoff, which is generated by precipitation events after wildland fires. Therefore, predicted precipitation events are crucial to the successful treatment selection. Future precipitation events can be estimated by using previous weather data, such as NOAA Atlas (NOAA, 2008) or PRISM (Daly, 2007). The probability of treatment success should consider the design storm (i.e., future precipitation events), design life of the treatments, and the recovery period following the fire. To calculate the chance of success of the treatment, Stream Notes (October, 1998; after Schmidt, 1997) can be used (table 10).

[Table 10. Calculated risk table (recurrence interval in years) (after Schmidt, 1987)]

3.3.5 Post-fire Runoff Increase

Based on the design storm, post-fire runoff increase is estimated. Each BAER team uses their preferred method. The interview survey showed that a majority of BAER specialists use the following methods, ranked from high to low (table 8): (1) USGS Regression, (2) Curve Number, (3) Rule of Thumb by Kuyumjian, (4) Water Erosion Prediction Project (WEPP) Model, (5) Fire-Enhanced Runoff and Gully Initiation (FERGI) Model. Detailed information on each method is in section 3.4 *Post-fire Runoff and Sediment Estimation.*

3.3.6 Capacity of Existing Road Structures

If existing road structures can handle the increased post-fire peak flow, no further treatment is needed. However, in some cases, the existing road structures can not handle the increased flow, and they should be removed or upgraded if the values at risk warrant the expected expense. Also many BAER specialists recommended considering a bulking factor to account for debris and sediment delivered with increased runoff from the burned upland area. Typical bulking factors range from 0.1 to 0.25.. Limited information exists on road structure capacities, and estimates must be made using on site measurements and calculations. Road structures such as culvert and rolling dip/water bar are further discussed in section 3.5 *BAER Road Treatments*, section 3.6.6 *Culvert Sizing*, and 3.6.7 *Rolling Dip/Water Bar*.

3.3.7 Choosing a Road Treatment

Post-fire road treatments should be implemented after considering the factors discussed above. The interview survey showed that BAER specialists use the following treatments,

ranked from high to low (table 9) (1) rolling dips/water bars/cross drain, (2) culvert upgrading, (3) ditch cleaning, armoring, and (4) culvert removal.

3.4 Post-fire Runoff and Erosion Estimation

To prescribe road treatments, it is essential to determine whether the existing drainage structure can handle the post-fire runoff increase. There is extensive literature to indicate that streamflow increases after fires through a combination of hydrologic processes summarized in table 11.

[Table 11. Changes in hydrologic processes caused by wildfires (Neary and others, 2005).]

There is a general consensus that post-fire streamflow can increase, often with orders of magnitude larger than pre-fire events, especially for watersheds of high and moderate burn severity. Burned watersheds can yield runoff quickly producing flash floods. The largest post-fire peak flow often occurs in smaller watersheds. Bigio and Cannon (2001) reported that specific discharges were the greatest from relatively smaller watersheds (< 0.4 mi^2) with an average discharge of 17,700 cfsm (cfs/ mi^2) or 28 cfs/acre, while discharges from the next larger sized watersheds (0.4 mi^2 to 4 mi^2) averaged 2,100 cfsm. Increased post-fire flow may transport debris that was produced by the fire. Often the post-fire peak flow is a combination of water flow and debris called bulking. Road treatments should be prescribed and implemented if existing drainage structures can not handle the post-fire runoff increase.

BAER specialists have been using several methods to estimate post-fire runoff: USGS regression, curve number, rule of thumb, ERMiT, FERGI, and WATBAL. Each of these methods are discussed below.

3.4.1 USGS Regression Methods

The USGS regression method is the most commonly used post-fire runoff estimation method by BAER team members (43%; table 8).

The Department of Interior U.S. Geological Survey (USGS) has developed a method to estimate magnitude and frequency of floods of both gaged and ungaged streams. The flood-frequency relations at gaged and ungaged sites were developed for various hydrologic regions, based on their stream gage records, basin characteristics, and numerous studies throughout the U.S. These flood-frequency relations are often called and expressed as a form of “USGS regression equations”, since a regression analysis was used to develop the flood frequency relations.

Input Requirement

To use the USGS regression method, the following information is required:

- USGS regression equations for the area of interests (burned sites);
- Gaged data from the watershed of interests (if any);
- Basin characteristics, such as the drainage area, elevation, precipitation, free water-surface evaporation, latitude, longitude, forest and herbaceous cover, high

elevation area, channel slope, soil storage capacity and permeability, and minimum and maximum January temperatures. The actual required basin characteristics vary depending on the hydrologic regions. Fortunately not all of these characteristics are required for a single region;

- Design storm intensity, duration, and recurrence interval;
- Size of high soil burn severity areas; and,
- Water repellency and surface runoff increase of high/moderate soil burn severity area, which should be determined by users.

Program Availability

USGS regression equation methods have been incorporated into StreamStats (USGS, 2007), which is a web-based tool to obtain streamflow information. StreamStats are available for many states, and are being implemented for the others (figure 1). Users can access StreamStat online (http://water.usgs.gov/osw/streamstats/index.html), and estimate peak flow at a given location.

[Figure 1. Availability of StreamStats for the U.S. (USGS, 2007).]

How to Use

The following steps are used to apply the USGS regression method for estimation of post-fire peak flow:

1. Find the USGS regression equations for the area of interest;
2. Collect the basin characteristics of burned areas;
3. Collect information about the burned area, such as percentage of high and moderate soil burn severity areas;
4. Determine design/damaging storm, including storm intensity, duration, and recurrence interval;
5. Estimate pre-fire runoff assuming no fires and unburned area for the area of interests;
6. Determine the percent runoff increase for high and moderate soil burn severity area compared to pre-fire runoff (a difficult step, as describe below);
7. Determine *modifier* that is defined as a ratio of post-fire to pre-fire runoff, and calculated as follows:

$$modifier = 1 + \frac{Percent\ runoff\ increase}{100\ \%} \times \frac{(A_H + A_M)}{A_T} \qquad \text{(Equation 1)}$$

where

A_H = high burn severity area within the watershed (L^2);
A_M = moderate burn severity area within the watershed (L^2), and;
A_T = total watershed area (L^2).

8. Estimate post-fire runoff by multiplying the modifier and pre-fire runoff.

Discussion

Since there are very limited studies and guidelines to determine the modifier or the percent runoff increase for high and moderate burn severity, often BAER team members rely on simple rules of their own. For example, some Region 1 BAER specialists used 100% runoff increase (double the runoff amount) for high/moderate soil burn severity areas in the first year of the fire, such as the 2006 Derby Fire (Story and others, 2006). Also they assumed 1/3 and 1/6 soil water repellency with 10 times surface runoff increase for high soil burn severity areas for the same year and for one year after the 2000 Skalkaho/Valley Complex Fires, Montana (unpublished data, Story, 2002).

Some BAER team members in Region 1 skipped steps 6–8, and used a USGS Water-Resources Investigations Report (Parrett and others, 2004) to estimate post-fire peak flow for their burned areas. This report provided post-fire runoff responses one year after from three burned areas from Montana (Canyon Ferry, Ashland, and Bitterroot Fires). Once the BAER team members chose a design storm and a station of which drainage area size was similar to their burned area, they could determine the matching post-fire peak flow for their burned areas. However, the report by Parrett and others (2004) did not provide information about size of burned areas and burn intensities within watersheds. Care should be taken when using a USGS report to estimate post-fire peak flow for burned areas without more detailed burned area conditions.

Advantages

The following were advantages to apply the USGS regression method for post-fire runoff and erosion estimation.

- Applicable for estimating both pre-fire and post-fire peak flow.
- Estimate peak flow, regardless of the storm duration and intensity.
- Appropriate for larger watersheds greater than 5 square mile.
- Does not usually require detailed watershed information, such as soil and topography.
- More accurate if gaged data is used from the watershed of interest.
- Applicable to longer duration events, and snowmelt runoff events.

Disadvantages

The following were disadvantages to apply the USGS regression method for post-fire runoff and erosion estimation.

- Does not estimate erosion.
- Does not consider post-fire debris flow/torrent.
- The user has to find the adequate USGS regression equations for the watershed in the pre-fire condition.
- The user has to find the adequate USGS regression equations for the watershed in the post-fire condition (if any).
- The user has to determine the modifier, or the soil water repellency and post-fire runoff increase for high and moderate burn severity areas.
- Uses only English units.

Example

The Bitterroot National Forest had Skalkaho/Valley Complex Fires in 2000, and had a 10 year-24 hour storm event on 1 September 2001. It was assumed that 1/3 of the high soil burn severity areas had soil water repellency, and a 10 times increase in surface runoff. USGS regression method (Omang, 1992) was used to calculate peak flows in the unburned condition. Observed and estimated peak flows are provided in table 12.

[Table 12. Comparison of observed and estimated peak flows using USGS regression method from 10 year-24 hour storm event one year after the 2000 Skalkaho/Valley Complex Fires in the Bitterroot National Forest, Montana (unpublished data, Story, 2002).]

Plotting percent of high soil burn severity area and observed post-fire peak flow shows that they are somewhat related (r^2=0.47) (figure 2). Figure 3 shows that observed post-fire peak flow does not match estimated post-fire peak flow, assuming 1/6 soil water repellency with 10 times surface runoff increase for high soil burn severity areas. Better soil water repellency effects should be developed and moderate soil burn severity areas should be considered for inclusion in the estimation.

[Figure 2. High burn severity area and observed post-fire peak flow (10 year-24 hour) from the 2000 Skalkaho/Valley Complex Fires in the Bitterroot National Forest, Montana (unpublished data, Story, 2002).]

[Figure 3. Observed and estimated post-fire peak flow (10 year-24 hour) from the 2000 Skalkaho/Valley Complex Fires in the Bitterroot National Forest, Montana (unpublished data, Story, 2002). Estimated post-fire peak flow does not match observed flow.]

Detailed information about how to use the USGS regression methods can be found in Appendix C.

3.4.2 Curve Number Methods

The NRCS curve number methods are the second most commonly used post-fire runoff estimation method by BAER team members (30%; table 8).

The curve number method was developed by the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS), to estimate runoff depth. It considers rainfall, soils, cover type, treatment/conservation practices, hydrologic conditions, and topography (slope steepness). Users have to choose a curve numbers (CN) based on cover type, treatment, hydrologic conditions, and Hydrologic Soil Group to estimate runoff and peak flow; therefore, the curve number is a single most important parameter in this method.

Input Requirement

To use NRCS curve number methods, the following information is required (USDA SCS, 1991):

- Drainage area (A) in square feet, square miles, or acres;
- Rainfall amount (P) for a storm duration of 24 hours, with a given recurrence interval;
- Hydrologic Soil Groups (A, B, C, and D) (table 13) that the watershed soil is classified into;
- Average watershed slope (Y) in percent;
- Flow length (*l*), the longest flow path, from the watershed divide to the outlet, in feet; and,
- Pre-fire and post-fire runoff curve numbers (CNs).

[Table 13. Description of NRCS Hydrologic Soil Group (USDA SCS, 1991)]

Program Availability

There are two CN methods that BAER teams frequently use. WILDCAT4 (Hawkins and Greenberg, 1990) is a MS DOS program, and FIRE HYDRO (Cerrelli, 2005) is an EXCEL spreadsheet. The WILDCAT4 is a storm runoff/hydrograph model, using triangular unit hydrographs. The WILDCAT4 model requires the following information:

- Name of the watershed,
- The average land slope (%) and the length of the longest channel (ft) or the time of concentration (hr),
- The area (acre) of Hydrologic Response Unit (HRU which is an area having a consistent hydrologic response),
- The CN of HRU,
- Storm duration (hrs),
- Storm rainfall depth (inches), and
- Storm distribution type, either SCS Type II (figure 4), Farmer-Fletcher (for central and north-central Utah; Farmer and Fletcher, 1972), uniform, custom, or generic. If a 'Generic' distribution is chosen, the following information is needed the minimum and maximum storm intensities (as a percent of the mean storm intensity), and the timing of the peak flow intensity (as a percent of the storm duration).

[Figure 4. Approximate geographic boundaries for SCS rainfall distributions (USDA SCS, 1991).]

The WILDCAT4 should be applied to watersheds of 5 square miles or less. The WILDCAT4 main menu, watershed data, storm data, and summary output screens are shown in figures 5 to 7.

[Figure 5. WILDCAT4 main menu screen.]
[Figure 6. WILDCAT4 watershed data screen.]
[Figure 7. WILDCAT4 storm data screen.]

[Figure 8. WILDCAT4 summary output screen.]

The WILDCAT4 is easy to use. However, the user has to specify the CN of pre- and post-fire conditions, and the program runs in DOS. WILDCAT5, a Windows version of WILDCAT program, is in development, and will be released in the near future (personal communication, Hawkins, 2008).

Cerrelli (2005) developed a spreadsheet, called FIRE HYDRO, to assist NRCS and Forest Service personnel to estimate design peak flows for the burned areas of Montana. The FIRE HYDRO is a peak flow analysis tool for the 2, 5, 10, 25, 50, and 100 year, 24 hour rainfall-runoff events for the pre- and post-fire conditions. The required input data includes the following drainage area (acre); average watershed slope (%); CN; and 2 to 100 year, 6 and 24 hour rainfall depths which are available from the NOAA web site (2008). The 6 and 24 hour rainfall depths are required to determine SCS rainfall distribution type (Type I, IA, II, or III) (figure 4). Most of Region 1, including Montana, has Type II that produces the highest peak flow among the SCS rainfall distribution types. The FIRE HYDRO spreadsheets are shown in figure 9 to 11. Cerrelli (2005) assumed that the runoff curve numbers of *bare soil* cover type or *poor* hydrologic condition for post-fire conditions. However, there is no clear guideline to choose post-fire runoff curve numbers. The FIRE HYDRO is applicable for 24 hour rainfall events only, and is not applicable for short duration rainfall events, such as one hour storm or less.

[Figure 9. Explanatory section of Fire Hydro (Cerrelli, 2005), an EXCEL spreadsheet to assist to estimate peak flows for the burned areas of Montana.]
[Figure 10. Runoff Curve Number (CN) section of Fire Hydro (Cerrelli, 2005), an EXCEL spreadsheet to assist to estimate peak flows for the burned areas of Montana.]
[Figure 11. Input and output section showing pre-fire and post-fire peak flow of Fire Hydro (Cerrelli, 2005), an EXCEL spreadsheet to assist to estimate peak flows for the burned areas of Montana. The 5,000 acre drainage area had a pre-fire 25 year peak flow of 186 cfs with a CN of 58 and post-fire peak flow of 1,088 cfs with a CN of 77, calculated from figure 9.]

Discussion

There are limited numbers of studies that provide post-fire runoff curve numbers. Springer and Hawkins (2005) attempted to provide a guideline to choose post-fire runoff curve number based on the 2000 Cerro Grande Fire, New Mexico and concluded that "*the post-fire trends in CN and peak flows are not readily explained and will be a topic of future research.*"

Livingston and others (2005) provided a guideline to choose the post-fire runoff numbers with a range of values as seen in table 14. They used computed CNs and compare pre- and post-fire CNs for 31 small (0.12 to 2.5 square miles) subbasins in the Los Alamos area and 24 small (0.11 to 2.3 square miles) subbasins affected by the 2002 Long Mesa Fire at Mesa Verde National Park, Colorado. To classify the soil burn severity of the whole watershed/basin, they used Wildfire Hydrologic Impact (WHI), based on the

percentage of high and moderate soil burn severity, as seen in table 15 and figure 12, and a general relation between pre- and post-fire CN ratio as seen in figure 13. Post-fire runoff CN can be estimated using this figure if pre-fire CN is known. Pre-fire CN should be determined by users using various sources such as table D.2 and D.3 in Appendix D. Their study results are applicable to the Los Alamos area and other areas in the southwest with similar pre-fire CN values and hydrology; however, they are less applicable to areas with different pre-fire rainfall and runoff characteristics.

[Table 14. Post-fire curve numbers (CNs) for various burn severities (Livingston and others, 2005)]

[Table 15. Variations in Wildfire Hydrologic Impact (WHI) classification due to high soil burn severity (Livingston and others, 2005)]

[Figure 12. Wildfire Hydrologic Impact (WHI) for small burned subbasins as a function of soil burn severity (Livingston and others, 2005).]

[Figure 13. General relation between pre- and initial post-fire curve number (CN) ratio for indicated Wildfire Hydrologic Impact (Livingston and others, 2005).]

[Table 16. Post-fire curve numbers (CNs) for various burn severities based on the Bitterroot National Forest, Montana (Cerrelli, 2005)]

An experienced BAER team member in Region 1 suggests using a CN of 90–95 for high soil burn severity without water repellent soils, and 93–98 for high soil burn severity with water repellent soils (e-mail circulation, Story, 2003). The Livingston CN values are within the range suggested by Story.

Cerrelli (2005) provided a guideline to select post-fire CN based on burn severity and hydrologic soil grouping specific to the Bitterroot National Forest wildfires (table 16). His initial search of the literature for CN values for burned areas in southwestern Montana was did not find appropriate CNs. Consequently, Montana NRCS engineers created a guideline based on the existing NRCS CN/land use table (e.g., table D.2 and D.3). However, no gaging or calibrating took place to verify or improve this guideline. The 2-year to 5-year, 24-hour storm events occurred in the following spring and summer. Runoff from these storm events did not cause failure of the protection practices assessed and implemented using this CN guideline (Cerrelli, 2005).

Since there are very limited studies and guidelines to choose CNs for post-fire conditions, often BAER team members use simple rules of their own. Details on these rules are in Chapter 3.6.2 *NRCS CN Methods*. For example, on Salt Creek BAER Hydrology Special Report (Higginson and Jarnecke, 2007), they used the following rules to determine post-fire CNs.

- High burn severity CN = pre-fire CN + 15
- Moderate burn severity CN = pre-fire CN + 10
- Low burn severity CN = pre-fire CN + 5
- Maximum CN value is 100.

Once the user has determined CNs for each HRU within a watershed, the problem of how to combine them arises. Curve Numbers and runoff depth are not linearly related, but curvilinearly related (Grove and others, 1998). A weighted average of all CNs in a watershed is commonly used to reduce the number of calculations. The underestimation of runoff using weighted average CNs is most severe for wide CN ranges, as would occur in watersheds containing low and high severity burns. Low CN values and low precipitation depths, as would occur in unburned southwestern watersheds would result in underestimation of runoff. Therefore, care should be exercised when applying weighted average CNs.

Another approach is to use distributed CNs in a GIS application. However, White (1988) and Stuebe and Johnson (1990) reported that using distributed CNs resulted in as much as 100 percent higher runoff than when using weighted average CNs.

The preferred method to estimate runoff from watersheds with different CNs is to combine runoff amounts from each HRU.

Advantages

The following were advantages to apply the NRCS CN methods for post-fire runoff and erosion estimation.

- Applicable for input to methods that calculate peak flow.
- Two CN methods and models (WILDCAT4 and FIRE HYDRO) available for post-fire application.
- WILDCAT4 considers shorter duration storm (e.g., 15 minute) to 24-hour storm duration; therefore, adequate for the regions where the damaging storm is short duration, such as 15 or 30 minutes.

Disadvantages

The following were disadvantages to apply the NRCS CN methods for post-fire runoff and erosion estimation.

- Does not estimate erosion.
- Does not consider post-fire debris flow/torrent.
- Applicable to smaller watersheds, which are less than 5 square miles.
- FIRE HYDRO only considers 24-hour storm duration.
- The user has to determine pre-fire and post-fire CN that is a sensitive parameter; therefore, the estimated peak flow is subjective to users.
- No guidelines to determine post-fire CN except Region 1 and 3.
- Difficulty in combining runoff from areas of different CNs within a watershed. Instead, users interchangeably use a weighted average of all CNs in a watershed.
- Will likely underestimate runoff when applying weighted average of CNs for high burn severity area in arid weather conditions.
- Uses only English units.

Example

The Blackerby Fire on the Nez Perce National Forest near Grangeville, Idaho occurred in August 2005. On 19 May 2006 a 0.79 inch precipitation event with a 30 minute duration occurred over a portion of the burned area. The precipitation event was equivalent to a 25 year-30 minute storm event as determined from NOAA Atlas 2 (Miller and others, 1973).

The NRCS CN flood flow model results used in the BAER analysis (using FIRE HYDRO) were for a 25-year return event and based on the assumption of limited soil and vegetation regeneration during the first year after the fire. The observed flood discharge value was 71 cfs or 56 cfsm (cfs per sq. mile). This observed flood discharge was half that of predicted flow. Additionally, the observed debris flow discharge was 620 cfs or 492 cfsm, indicating that debris flow discharge was nearly an order of magnitude greater than the flood discharge. Details are in Chapter 3.6.2 *NRCS CN Methods*.

Detailed information about how to use the NRCS curve number methods can be found in Appendix D.

3.4.3 Rule of Thumb by Kuyumjian

The rule of thumb by Kuyumjian has been used by Region 3 BAER team members, which is about 10% of BAER interviewees (table 8).

Experienced BAER team members often use their own rule of thumb, which was developed based on their experience and post-fire monitoring/observation, and works well within certain regions. An experienced BAER hydrologist (personal communication, Kuyumjian, 2007) suggested using the following rule of thumb, which requires a minimal amount of input information.

Input Requirement

To use the rule of thumb by Kuyumjian, the following information is required:

- Area of high and moderate soil burn severity area; and,
- Anticipated precipitation amount from damaging storm.

How to Use

The following steps are used to apply the rule of thumb by Kuyumjian for estimation of post-fire peak flow:

1. Determine design/damaging storm, including storm intensity, duration, and recurrence interval;
2. Estimate post-fire peak flow (Q_p) using the following relationship:

$$Q_p = 300 \times A_s \times I \times 1.25 \qquad \text{(Equation 1)}$$

where

Q_p = peak flow in cfs;
I = precipitation intensity in inch/hour;
A_s = size of high and moderate burn severity area in square miles; and,
1.25 = bulking factor.

Discussion

The rule of thumb by Kuyumjian is similar to the rainfall-discharge relation that was determined for 31 data pairs in 2001 and 17 data pairs in 2002 from seven sub-watersheds in the Rendija Canyon watershed after the 2000 Cerro Grande Fire (Moody and others, 2007). About 82% of the Rendija Canyon watershed was severely burned. Their analysis was based on the change in the normalized burn ratio (ΔNBR; Key and Benson, 2006), which incorporates reflectance measurements from Landsat imagery and was designed to measure the fire effects on vegetation and soil characteristics. Watersheds with 581 ± 5% can be categorized as high or moderate-high burn severity (Cocke and others, 2005; Key and Benson, 2006). The rainfall-discharge relation was

$$Q_u^{peak} = b \cdot (I_{30} - I_{30}^{thresh}) \quad I_{30} > I_{30}^{thresh} \qquad \text{(Equation 2)}$$

where

Q_u^{peak} = peak flow per unit area (inch h^{-1});
b = unit-less constant;
I_{30} = 30 minutes rainfall intensity (inch h^{-1}); and,
I_{30}^{thresh} = the largest value of I_{30} below which no surface flow occurs (inch h^{-1}).

Moody and others (2007) reported *b* and I_{30}^{thresh} values as shown in table 17.

[Table 17. *b* and I_{30}^{thresh} values in the rainfall-discharge relation from the Rendija Canyon watershed after the 2000 Cerro Grande Fire, New Mexico (Moody and others, 2007).]

The rainfall-discharge relation can be used to compare the rule of thumb by Kuyumjian. Using combined b and I_{30}^{thresh} values from table 17, assuming I_{30} » 8.5 mm h^{-1} (0.33 inch h^{-1}), and that entire drainage area was high severity burn area, equation 2 can be reduced to

$$Q^{peak} = 303 \times A_s \times I_{30}, \qquad \text{(Equation 3)}$$

which is very close to the rule of thumb by Kuyumjian without the bulking factor of 1.25.

Advantages

The following were advantages to apply the rule of thumb by Kuyumjian for post-fire runoff and erosion estimation.

- Applicable for estimating post-fire peak flow.
- A simple and quick approximation.
- Does not need to determine parameter values.
- Considers bulking factor for post-fire debris flow/torrent.

Disadvantages

The following were disadvantages to apply the rule of thumb by Kuyumjian for post-fire runoff and erosion estimation.

- Does not estimate erosion.
- Only for short-duration (one hour or less) high intensity (greater than 0.5 inch) storms.
- Not applicable for estimating peak flow from snowmelt or rain-on-snow or frozen ground.
- Currently evaluated only for Region 3.
- Uses only English units.

Example

> Approximately 4.8 square mile of the Rendija Canyon watershed was burned by the 2000 Cerro Grande Fire: 82% at high severity, 10% at moderate severity, 6% at low severity, and 2% was unburned (Gallaher and Koch, 2004). Seven subwatersheds were monitored for rainfall intensity and discharge in 2001 and 2002 (Moody and others, 2007). Four subwatersheds had 581 ± 5% of ΔNBR value that was considered high or moderate-high burn severity (Cocke and others, 2005; Key and Benson, 2006).

Assuming the entire drainage area was high severity burn area, peak flow per unit drainage area (cfs mile^{-2}) can be calculated based on rainfall intensity which is greater than 0.5 inch. The rule of thumb by Kuyumjian estimated less than a half (47%) of peak flow within ± 50% of observed values (table 18), which can be from uncertainty associated with discharge and rainfall intensity measurements or natural variation that the rule of thumb can not consider.

[Table 18. Comparison of observed and estimated peak flow using Kuyumjian's rule of thumb from various rainfall intensities (> 0.5 inch h^{-1}) for 2001 in four high severity burn subwatersheds of Rendija Canyon after the 2000 Cerro Grande Fire, New Mexico (Moody and others, 2007).]

3.4.4 TR-55

Seven of the BAER team members used TR-55 to calculate post-fire runoff increase (table 8).

The TR-55 requires the runoff curve number (CN) as an input parameter; therefore, it can be considered as a Curve Number method. The TR-55 was released as a simplified procedure to calculate the storm runoff volume, peakflow rate, hydrograph, and storage

volume for storm water management structures in small watersheds in urban areas, assuming the NRCS Type II rainfall distribution for all calculations (USDA SCS, 1975). Later a major revision was made to improve the model by adding three more rainfall distributions (Type I, IA, and III; figure 4), programming the computations, and estimating time of concentration using split separate flow phases (USDA SCS, 1986).

Input Requirement

Required input data is as follows (USDA NRCSb, 2005)

- Identification data;
- Dimensionless unit hydrograph;
- Storm data;
- Rainfall distribution;
- Area (acre);
- Runoff Curve Number (CN); and,
- Time of concentration (T_c) details.

Program Availability

The current version of TR-55 computer model is WinTR-55, which was revised and completely rewritten. It uses the TR-20 model (USDA NRCS, 2005a), another NRCS storm event surface water hydrologic model applied at a watershed scale, as the driving engine for all the hydrograph procedures (USDA NRCS, 2005b).

WinTR-55 is a single-event rainfall-runoff hydrologic model for small watersheds with multiple sub-areas that are homogeneous. It generates hydrographs from urban and agricultural areas; and the generated hydrographs are routed downstream through channels or reservoirs.

Discussion

WinTR-55 model can be run in either English or Metric units, and input data above uses English unit. The WINTR-55 model and related documents are available at NRCS web site, http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/WinTR55.html.

WinTR-55 model has the variables and their ranges are shown in table 19. For its applications on the BAER road treatments, the TR-55 should be run once for pre-fire watershed conditions, and again for post-fire conditions.

[Table 19. WinTR-55 variables and their ranges (USDA NRCSb, 2005).]

Advantages

The following were advantages to apply the WinTR-55 for post-fire runoff and erosion estimation.

- Applicable for estimating peak flow.
- Estimates time to peak.

- Applicable to larger watersheds, which are less than 25 square miles.
- Uses both English and metric units.

Disadvantages

The following were disadvantages to apply the WinTR-55 for post-fire runoff and erosion estimation.

- Does not estimate erosion.
- Does not consider post-fire debris flow/torrent.
- Only considers 24-hour storm duration; therefore, not applicable to the regions where the damaging storm duration is much shorter, such as 15 or 30 minutes.
- Applicable to smaller watersheds, which are less than 5 square miles.
- The user has to determine pre-fire and post-fire CN that is a sensitive parameter; therefore, the estimated peak flow is subjective to users.
- No guidelines to determine post-fire CN except Region 1 and 3.

Example

The TR-55 model was used to estimate post-fire peak flows on 2002 Bullock fire. Table 20 shows the analysis conducted. The "2 year post-fire equivalent" displays the corresponding flood level expected from a typical 2 year storm event. In other words, there is 50% chance of a storm event that might happen in any given year.

[Table 20. Hydrological analysis 2 year, post-fire equivalent flood level using TR-55 for the 2002 Bullock Fire in the Coronado National Forest, Arizona (Lefevre and others, 2002).]

3.4.5 Water Erosion Prediction Project (WEPP) Model: Erosion Risk Management Tool (ERMiT)

The ERMiT (Robichaud and others, 2006 and 2007), a FS WEPP Interface, has been used by the BAER team members (5%; table 8), primarily from Region 4.

The WEPP model was developed by an interagency group of scientists from the U.S. Department of Agriculture's Agricultural Research Service, Forest Service, and Soil Conservation Service (currently Natural Resources Conservation Service); the U.S. Department of Interior Bureau of Land Management; the U.S. Geological Survey; and several university cooperators. The WEPP model predicts soil erosion and sediment delivery by water using stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics (Flanagan and Livingston, 1995). The Forest Service WEPP (FS WEPP) Interfaces were developed by the USDA Forest Service Rocky Mountain Research Station, Soil and Water Engineering, Moscow, Idaho (Elliot, 2007). They are a user-friendly online tool for various forest applications, and consist of the following individual interfaces:

- Cross Drain: Predicts sediment yield from a road segment across a buffer;
- Rock:Clime: Creates and downloads a WEPP climate file;
- WEPP:Road: Predicts erosion from insloped or outsloped forest roads;
- WEPP:Road Batch: Predicts erosion from multiple insloped or outsloped forest roads;
- Disturbed WEPP: Predicts erosion from rangeland, forestland, and forest skid trails;
- Erosion Risk Management Tool (ERMiT): Predicts the probability associated with a given amount of soil erosion in each of five years following wildfire, and estimates effectiveness of various hillslope treatments; and,
- WEPP FuME (Fuel Management): Predict soil erosion associated with fuel management practices including prescribed fire, thinning, and a road network, and compares that prediction with erosion from wildfire.

Input Requirement

To use the ERMiT, the following information is required (figure 14):

- Climate;
- Soil texture, chosen among clay loam, silt loam, sandy loam, and loam;
- Rock content (%);
- Vegetation type, chosen among forest, range, and chaparral;
- Range/chaparral pre-fire community description, which can be defined by users if "range" or "chaparral" is selected for vegetation type;
- Hillslope gradient consists of top gradient, the steepness, in percent, of the upper portion of the hillslope; middle gradient, the steepness of the main portion; and, toe gradient, the steepness of the lower portion, the top and toe gradients each represent 10% of the hillslope length, and the middle gradient represents 80%;
- Hillslope horizontal length; and,
- Soil burn severity, chosen among high, moderate, and low.

[Figure 14. ERMiT input screen (http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/ermit/ermit.pl).]

Program Availability

The ERMiT is run from the web site (http://forest.moscowfsl.wsu.edu/fswepp/). Users can type and choose input information, and run ERMiT. The ERMiT reports rainfall event rankings and characteristics (including runoff), the exceedance probability associated with sediment delivery, and mitigation treatment comparisons, i.e., untreated, seeding, mulching with application rate of 0.5, 1, 1.5, and 2 ton/acre, erosion barriers, and contour-felled logs/straw wattles (figure 15).

[Figure 15. ERMiT output screen. It reports rainfall event rankings and characteristics (including runoff), the exceedance probability associated with sediment delivery, and mitigation treatment comparisons.]

Advantages

The following were advantages to apply the ERMiT for post-fire runoff and erosion estimation.

- Applicable for estimating post-fire erosion up to 5 years after the fire.
- Identify the damaging storm, which is often short duration (less than 1 hour) high intensity storm as many BAER team members described.
- Provides various outputs, such as the exceedance probability.
- Suitable for evaluating the effectiveness of various hillslope treatments, i.e., seeding, mulching, erosion barrier, and contour-felled log/straw wattle.
- User-friendly, easy to use, and on-line accessible.
- Process-based; i.e., applicable to any part of U.S. and to other countries as long as the required climate information is available.
- Uses both English and metric units.

Disadvantages

The following were disadvantages to apply the ERMiT for post-fire runoff and erosion estimation.

- Does not estimate post-fire peak flow; therefore, not adequate for prescribing post-fire road treatments.
- Does not provide pre-fire runoff and erosion information; therefore, can not compare pre- and post-fire changes.
- Does not consider post-fire debris flow/torrent.
- Does not consider watershed shapes, and assumes a rectangular hillslope; therefore, ERMiT is difficult for BAER team members to apply for post-fire conditions at a watershed scale (> 2 mile^2).

Recent developments now allow WEPP simulations using digital sources of information with Geographic Information Systems (GIS). This GIS wizard is called GeoWEPP (http://www.geog.buffalo.edu/~rensch/geowepp/), and it has been under development for forest conditions since about 2002 with funding from the Joint Fire Science Program (Renschler, 2003; Renschler, 2007). GeoWEPP will allow BEAR team members to model pre- and post-fire conditions at a watershed scale. See the GeoWEPP web site for current status of the program.

Example

The WEPP model was run for 20 years to estimate the pre- and post-fire runoff and erosion potential for Red Eagle Fire in 2006. The results shows more runoff events with greater risks of flood and erosion (table 21). The WEPP model predicted dramatic increase in number of rainfall and snowmelt runoff events from 2 and 0 for pre-fire conditions to 79 and 14 for post-fire conditions.

[Table 21. Runoff and erosion estimation using the WEPP model for the 2006 Red Eagle Fire, Montana (Sirucek and others, 2006).]

3.4.6 Fire-Enhanced Runoff and Gully Initiation (FERGI) Model

The FERGI model is used by 2% of the BAER team members in Region 4 (table 8).

The FERGI model was developed by the USDA Rocky Mountain Research Station, Boise Aquatic Science Lab, based on several scientific research papers (Rajagopalan and Lall, 1999; Shakesby and others, 2000; Istanbulluoglu and others, 2002; Istanbulluoglu and others, 2003; Istanbulluoglu and others, 2004; Rhodes, 2005; Luce and others, 2005; Luce, 2005). The FERGI model is physically-based mathematical description of hillslope hydrologic and geomorphic response to a given set of weather events; therefore, the model is applicable to any part of the western U.S. FERGI estimates the probability of post-fire rainfall excess (mm), runoff generation amount (m^3/s/m), and gully initiation positions (m) on hillslopes with and without mitigations, using contour felled logs/log barrier.

Input Requirement

To use the FERGI model, the following information is required:

- Location of three nearest weather stations selected from the FERGI input screen;
- Depth to water repellent layer (mm), the proportion of the area that is underlain by water repellent soils after a fire;
- Fractional water repellency (between 0 and 1);
- Saturated hydraulic conductivity (mm/hr);
- Slope (m/m);
- Hillslope length (m), average length of hillslope before flow begins to accumulate into channels;
- D_{50} of soil surface (mm);
- Storage capacity of barriers (mm), the amount of precipitation that can be stored by the barriers, i.e., the volume of water storage behind barriers divided by the total area over which the measured barriers are applied; and,
- Fraction of area trenched (between 0 and 1), the total length of scalping times the width of scalped area divided by the total area of the site.

Program Availability

The FERGI model is accessible from Forest Service intranet (http://fergi.boise.rmrs.fs.fed.us/fergi/index.html), and run online. Users follow three steps to run the FERGI model: 1) zoom to area of interest, 2) select each of the three weather stations (figure 16), and 3) type in soil and hillslope parameters (figure 17).

[Figure 16. FERGI weather input screen.]
[Figure 17. FERGI soil and hillslope input screen.]

The FERGI model reports the following (figure 18):

- Return interval (yrs; from 1 to 100 years);
- Rainfall excess no treatment (mm);

- Rainfall excess treatment (mm);
- Rainfall excess reduction (%);
- Hillslope runoff no treatment ($m^3/s/m$);
- Hillslope runoff treatment ($m^3/s/m$);
- Hillslope runoff reduction (%);
- Gully head no treatment (m);
- Gully head treatment (m); and
- Gully head reduction (%).

This output is provided as graphs (percent reduction of rainfall excess, hillslope runoff, and gully length) (figure 18) and tables of text file (.txt).

[Figure 18. FERGI output as hillslope runoff graph. Usage of contour felled logs/log barrier is mostly effective for small rainfall recurrence interval (less than 5 years).]

Advantages

The following were advantages to apply the FERGI for post-fire runoff and erosion estimation.

- Estimate rainfall excess, post-fire runoff, and gully length of a rectangular strip
- Provides an estimate of the effectiveness of contour felled logs/log barrier, as a function of storm return periods.
- On-line accessible.
- Process-based, and applicable to the western U.S.

Disadvantages

The following were disadvantages to apply the FERGI for post-fire runoff and erosion estimation.

- Does not provide pre-fire rainfall excess, runoff amount, and gully initiation positions; therefore, users cannot compare pre- and post-fire changes.
- Does not estimate erosion.
- Does not consider post-fire debris flow/torrent.
- Available only for Forest Service intranet.
- Requires detailed soil parameter information.
- Does not consider watershed shapes, and assumes a rectangular hillslope.
- Considers only 24-hour storm duration; therefore, not applicable to the regions where the damaging storm duration is much shorter, such as 15 or 30 minutes.
- Uses only metric units.

3.4.7 Watershed Response Model for Forest Management (WATBAL)

The WATBAL has been used by 2% of the BAER team members in Region 1 (table 8).

The WATBAL program originated from the Northern Region's Water Yield Guidelines, also known as R1/R4 Guidelines (Haupt and others, 1974) to establish water yields in response to cumulative watershed development and vegetation manipulation and recovery over time. The WATBAL program was written in FORTRAN, and has been evolved using up-to-date methodologies, research findings, and locally derived water/sediment data. The WATBAL program is currently designed to simulate the potential and most likely effects of primary forest management practices (e.g., timber harvest, road development, and fire) on the responses of watershed and water resources systems with regard to stream flow and sediment regimes (Jones, 2005). There are three functional elements in the program:

- A water yield model that utilizes response functions correlated to land characteristics and forest practices. These functions were from the Hydrologic Simulation Model of the Colorado Subalpine Forest (Leaf and Brink, 1973), and calibrated for the Northern Rocky Mountains;
- A sediment yield procedure based on surface erosion that incorporates the concepts and methodologies for the Idaho Batholith physiographic regions and associated lands (Cline and others, 1981); and
- A sediment yield procedure based on mass erosional processes developed on the Clearwater National Forest (Jones, 2005).

Typical WATBAL watershed input data file and watershed output response summary report are in figures 19 and 20.

[Figure 19. Typical WATBAL watershed input data file format (Personal communication, Foltz, 2008). Adding input data requires understanding of the program and the natural hydrologic and erosional processes.]
[Figure 20. Typical WATBAL watershed response summary report (Personal communication, Foltz, 2008). Interpretation of output data requires understanding of the program and the natural hydrologic and erosional processes.]

Advantages
The following were advantages to apply the WATBAL for post-fire runoff and erosion estimation.

- Applicable for estimating stream flow (i.e., annual and peak runoff, and time to peak) and sediment regime effects of forest management practices, including timber harvest, road development, and fire on watersheds.
- The Clearwater National Forest keeps monitoring watersheds. Based on the monitoring data, the model is continuously calibrated, validated, and calibrated again; therefore, believed to be relatively accurate.

Disadvantages
The following were disadvantages to apply the WATBAL for post-fire runoff and erosion estimation.

- Only applicable to Central and Northern Rocky Mountains for water yield (annual and peak runoff); the Idaho Batholith physiographic region for sediment yield from surface erosion; and Clearwater National Forest in the southern Idaho Batholith for sediment yield from landslides.
- Does not consider post-fire debris flow/torrent.
- Work best in watersheds of 4–40 square miles. It tends to over predict sediment in watersheds smaller than 4 square miles; and under predict, greater than 40 square miles (Jones, 2005).
- Program is not user-friendly.
- Uses only English units.

Example

The Crooked Fire occurred on the Clearwater National Forest in July 28, 2000. WATBAL was used to estimate post-fire sediment and peak flow increases. The pre- and post-fire WATBAL comparison is are shown in table 22.

[Table 22. Pre- and post-fire WATBAL comparison for the 2000 Crooked Fire in the Clearwater National Forest, Idaho, based on fire perimeter as of August 28, 2000. All values are percent increase over baseline condition (Jones, 2000).]

3.5 BAER Road Treatments

The BAER specialists have been using various road treatments to increase flow and debris flow capacity of road drainage structures due to wildland fires. Depending on regional climate and fire regimes, different road treatments were preferred. Each of the popular road treatments is discussed in alphabetical order below. Napper (2006) describes details of most of these treatments, including primary use, description, purpose, suitable sites, cost, and construction specifications.

3.5.1 Armored Ford Crossing

An armored ford crossing prevents stream diversion and keeps water in its natural channel; it prevents erosion of the road fill and reduces adverse effects to water quality; and it maintains access to areas once storm runoff rates diminish. Only small fraction of BAER specialists recommended armored ford crossing.

3.5.2 Channel Debris Cleaning

Channel debris cleaning above the culvert is the removal of organic debris and sediment deposits to prevent them from becoming mobilized in debris flows or flood events. Channel debris cleaning is not frequently recommended by BAER specialists.

3.5.3 Culvert Inlet/Outlet Armoring/Modification

Culvert inlet/outlet is often armored to protect the culvert inlet and fillslope. Culverts are modified to increase the flow and debris passage capacity to prevent road damage. Flared/winged metal end sections are often attached for these purposes, especially in California. Only very small fraction of BAER specialists recommended these treatments. Culvert modification is not commonly recommended by the BAER specialists in the other areas.

3.5.4 Culvert Removal

Culvert removal incorporates each Forest's guidelines for hydraulic capacity of the culvert. If vehicle access is not need, often temporary culvert removal is an option until the area stabilizes. Culvert removal is frequently recommended by Region 3 and 6 BAER specialists.

3.5.5 Culvert Risers

Culvert risers help prevent the culvert from plugging with sediment and floating debris. The risers allow sediment to accumulate and still allow the water to flow through the culvert. Storage of water and sediment also reduce the peak flows. Only Region 5 BAER specialists recommended culvert risers on a small number of occasions.

3.5.6 Culvert Upgrading

Culvert upgrading incorporates each Forest's guidelines for both hydraulic capacity of the culvert and any requirements for aquatic species passage. Given the values at risks, the culvert upgrading must be designed and implemented to maintain vehicle access and protect aquatic resources. Culvert upgrading is the second most frequently recommended

BAER road treatment. Flow capacity of typical culverts in forestlands is shown in table 23.

[Table 23. Flow capacity for circular and pipe-arch culverts (Landowners Reference Manual, 1994; Robison and others, 1999)]

3.5.7 Debris/Trash Rack

A debris/trash rack is a barrier across the stream channel to stop debris too large to pass through a culvert. Debris/trash racks are designed for small and medium floating debris. The storage area upstream from the debris/trash rack should be large enough accumulate the anticipated size and quantity of debris, and be accessible for clean-out equipment. Only Regions 3 and 5 BAER specialists recommended debris/trash racks frequently whereas other Regions only occasionally recommended them.

3.5.8 Ditch Cleaning/Armoring

Ditches are cleaned to prevent culvert plugging, and armored to prevent erosion from the ditch bed. Many BAER specialists considered ditch cleaning/armoring as an efficient road treatment and, consequently, frequently recommend it.

3.5.9 Hazard/Warning Sign

Hazard/warning sign informs the public of potential hazards created by the fire including flooding, falling rock, and debris. Stocking hazard/warning signs for immediate use in advance of the fire season is useful.

3.5.10 Outsloping Road

An outsloped road design disperses water along the fillslope and can reduce erosion. Outsloping is often combined with other road treatments, such as rolling dip and armored ford crossing. Outsloping is not frequently recommended by BAER specialists.

3.5.11 Relief Culvert

Additional relief culvert is sometimes considered to increase flow capacity of water and debris for an existing culvert. Relief culvert is not frequently recommended by BAER specialists.

3.5.12 Road Closure

Road closure is intended to prevent unacceptable degradation of critical natural or cultural resources or downstream values. Region 3 BEAR specialists considered road closure as an alternative to other road treatments in the events of flash flooding, to protect possible road users. However, road closure is generally not liked by the public. Road closure is seldom recommended.

3.5.13 Road Decommissioning

Road decommissioning is intended to restore natural hillslope, and reduce degradation of natural resources and downstream values. Road decommissioning is seldom recommended, however, it is a viable treatment in cases where roads are either not part of the classified road system, or where roads have gone through a process (usually including

public involvement) that clears restrictions for decommissioning. Classified roads are not eligible for road decommissioning using BAER fund. There are five levels of treatments for road decommissioning: (1) block entrance, (2) revegetation and waterbarring, (3) remove fill and culverts, (4) establish drainage ways and remove unstable road shoulders, and (5) full obliteration recontouring and restoring natural slopes (USDA Forest Service, 2003). If road decommissioning is prescribed in BAER, it is usually at the level of full recontouring.

3.5.14 Rolling Dip/Water Bar

Rolling dip/water bar is used to drain water effectively from the road surface and reduces the concentration of flow. Rolling dip/water bar also provides a relief valve when a culvert is plugged. Often rolling dip/water bar is armored, and used instead of a culvert upgrade because of its relatively low cost. Rolling dip/water bar is the most frequently recommended road treatment by BAER specialists.

However, rolling dip/water bar may be eroded away with strong currents in high discharge. Tables 24 and 25 show the permissible velocity to withstand erosion and the permissible velocity in vegetated channels. The dipped road surface must be able to withstand these flow velocities.

[Table 24. Permissible velocity to withstand erosion (Watkins and Fiddes, 1984; Novak and others, 2001).]

[Table 25. Permissible velocities in vegetated channels (Watkins and Fiddes, 1984).]

The overflow discharge over an embankment, such as a drain dip located in the fill over a culvert can be estimated using the weir formula in equation 4.

$$Q = C\, b\, H^{3/2} \qquad \text{(Equation 4)}$$

where

Q = discharge over an embankment, in $m^3\ s^{-1}$;
C = still coefficient, in $m^{1/2}\ s^{-1}$;
b = length of the flow section in m; and,
H = total head upstream of the still in m.

The coefficient of C is a function of h/L (h is the head over a still of width L) for free flow conditions; whereas a correction factor, f, as a function of $h_{d/s}/H$ ($h_{d/s}$ is the head drop of a sill to downstream), may be incorporated in equation 4 for submerged flow conditions (Novak and others, 2001). Free flow occurs where a man-made structure creates a drop in water level over the structure resulting in the major part of the total upstream energy head being converted into kinetic energy to obtain critical flow at the control section. In this condition the upstream head is independent of downstream conditions. The opposite of free flow is submerged flow. In submerged flow the drop in water level over the structure is small, the flow above it remains sub-critical; therefore, the upstream head is affected by downstream conditions (Boiten, 2002). Either of these

flow conditions is possible in forest conditions. The range of values for *C* and *f* are shown in tables 26 and 27.

[Table 26. Range of values of C for free flow or modular flow over the embankment (Novak and others, 2001).]

[Table 27. Correction factor, *f* for submerged flow or non-modular flow (Novak and others, 2001).]

3.5.15 Storm Patrol

A storm patrol is to keep culvert and drainage structures functional by cleaning sediment and debris from the inlet between or during storm events. It is an efficient measure to protect the transport infrastructure after a wildfire, and provides needed road access throughout the designated storm season by ensuring road drainage function.

3.6 Gray Literature from BAER Interviews

From BAER interviews, we obtained various gray literature, i.e. unpublished reports, file reports, or hard to find proceeding papers. Table 28 lists and categorizes the gray literature. This section contains a summary of beneficial information related to post-fire runoff and erosion estimation methods, road treatments, and post-fire monitoring reports. Opinions and values in the summaries below are those of the gray literature's authors and not necessarily those of this report's authors. In a few instances, italicized comments reflect what we believed necessary to clarify or correct comments in the gray literature.

[Table 28 List of gray literature obtained from BAER interviews]

3.6.1 USGS Regression Methods

Parrett, Charles; Cannon, Susan H.; Pierce, Kenneth L. 2004. Wildfire-related floods and debris flows in Montana in 2000 and 2001. Water-Resources Investigations Report 03-4319. Denver, CO: U.S. Geological Survey. 22 p.

Following extensive wildfires in summer 2000, flooding and debris flow occurred in three different burned areas in Montana on the Canyon Ferry, Ashland, and Bitterroot Fires (figure 21).

[Figure 21. Location of three burned areas in Montana: A. Canyon ferry, B. Ashland, and C. Bitterroot (Parrett and others, 2004).]

Approximately 40,000 acres were burned through September in the Canyon Ferry area. Fires included Canyon Ferry Complex and Boulder Complex (Montana Department of Commerce, 2003). A U.S. Geological Survey rain gage recorded a 5 to 10 year return period, 15 minute duration event on July 17 on Crittenden Gulch. The resulting measured flow had a pre-fire 200 year return interval. Details of precipitation and peak streamflow discharges are shown in tables 29 and 30.

[Table 29. Data from significant precipitation storm events during 2001 at U.S. Geological Survey precipitation stations in Canyon Ferry area, Montana (Parrett and others, 2004).]
[Table 30. Peak streamflow discharges and estimated recurrence interval during 2001 at U.S. Geological Survey streamflow-gaging stations in Canyon Ferry area, Montana (Parrett and others, 2004).]

Approximately 60,000 acres were burned in the Ashland area. Fires included Pease Fire (Montana Department of Commerce, 2003). The U.S. Geological Survey rain gage recorded a 100 to 500 year return period, 5 minute duration event on June 30 at a site (site 33) near the center of the Ashland area (table 31). Recurrence intervals for calculated peak stream discharges, based on unburned conditions, were 50−100 years at three sites and greater than 500 at five sites (table 32).

[Table 31. Data from significant precipitation storm events during 2001 at U.S. Geological Survey precipitation stations in Ashland area, Montana (Parrett and others, 2004).]

[Table 32. Peak streamflow discharges and estimated recurrence interval during 2001 at U.S. Geological Survey streamflow-gaging stations in Ashland area, Montana (Parrett and others, 2004).]

The Bitterroot area was the most active of the 2000 fire season, and included six different fire complexes, including Valley Complex , Mussigbrod Complex, Skalkaho Complex, Wilderness Complex, Middle Fork Complex, and Blodgett Trailhead. More than 400,000 acres were burned in the Bitterroot area (Montana Department of Commerce, 2003). A series of thunderstorms in July 2000 caused flooding and debris flows on small streams. The U.S. Geological Survey rain gage recorded multiple 10 to 25 year return period, 5 to 30 minute duration events on June 15, 20, and 21. The resulting flows had an estimated pre-fire recurrence interval of 200 to 500 years. Details of precipitation and peak streamflow discharges are shown in table 33–35.

[Table 33. Data from significant precipitation storm events during 2001 at U.S. Geological Survey precipitation stations in Bitterroot area, Montana (Parrett and others, 2004).]

[Table 34. Peak streamflow discharges and estimated recurrence interval during 2001 at U.S. Geological Survey streamflow-gaging stations in Bitterroot area, Montana (Parrett and others, 2004).]

[Table 35. Peak debris-flow discharges on July 15, 2001 at selected tributary sites in the Sleeping Child Creek drainage in Bitterroot area, Montana (Parrett and others, 2004).]

Gerhardt, Nick. 2005. [Personal notes]. September 2. China 10—Flow calculations using USGS regression method.

- Assume that peak flow occurs in spring runoff, not fall storm flow.
- 10 year 24 hour storm = 2.8 inches (NOAA, 1973)
- Use 10 year peak flow for Peasley Creek from Kjelstorm and Moffat (1981) = 11.9 cfsm for pre-fire condition
- Assume 2 × 1st year post-fire runoff increase for moderate/high burn severity from Robichaud (2000)
- Calculate area of different burn severities as follows:

Area of burn	= 122 acre for high burn = 592 acre moderate burn	} 714 acre	= 1.12 mi^2	= 41%
	= 254 acre for low burn = 796 acre unburned	} 1050 acre	= 1.64 mi^2	= 59%
			2.76 mi^2	

- Calculate post-fire peak flow based on 10 year 24 hour storm as follows:
  Peak flow from high/moderate burn severity = 23.8 cfsm × 41% = 9.76 cfsm
  Peak flow from low burn severity/unburned = 11.9 cfsm × 59% = 7.02 cfsm
  16.78 cfsm

Jones, Richard; Mital, Jim. 2003. Burned area report, Beaver Lakes Complex. 11 p.
Jones, Richards; [and others]. 2006. Burned area report, Gash Creek Incident. 13 p.

For design storm analysis, 15 minute, 25 year storm was used that occurred in Sleeping Child Creek on July 15, 2001 (Parrett and others, 2004; table 33). The storm produced 200 cfs over 1.8 mi^2 burned watershed, resulting in 110 cfsm, which was greater than 500 year runoff event (Parrett and others, 2004; table 34). This watershed was selected for the design storm since the runoff did not include debris and the watershed size was small (< 2 mi^2). The burned watershed by the 2003 Beaver Lakes Fire, Idaho could receive a similar storm and respond similar to Sleeping Child Creek where burn intensities were high. Storm runoff should be adjusted where burn intensities are less than high. Road drainage structures for drainage area less than 2 mi^2 should be designed to handle these flows (110 cfsm or less). For watersheds of 5–20 mi^2, the design storm should be approximately 23 cfsm (Arkell and Richards, 1986).

Johnson, Steve; Gould, Jessica. 2003. Burned area emergency stabilization and rehab plan, Blackfoot Complex Fires, Flathead NF, watershed resource assessment. Libby, MT: U.S. Department of Agriculture, Forest Service, Northern Region, Kootenai National Forest. 10 p.

Table 36 shows the burned area acreages by fire severity for selected watersheds associated with Blackfoot Complex as of September 20, 2003. A USGS method based on Omang (1992) was used to estimate 100 year discharges for selected drainages (table 37). To estimate the potential watershed response from these areas, a *modifier* (flow increase factor) was applied to the USGS predicted pre-fire flow values. The percent of the basin that had either high or moderate burn severity was used as the modifier (e.g., 37% of high and moderate burn severity = 1.37 for modifier).

[Table 36. The burned acreages by fire severity associated with the 2003 Blackfoot Complex, Montana as of September 20, 2003 (Johnson and Gould, 2003).]
[Table 37. Predicted pre- and post-fire, 100 year flows based on Omang (1992) for the 2003 Blackfoot Complex, Montana (Johnson and Gould, 2003).]

Sirucek, Dean; Olson, Dennis; Butterfly, Henry; Johnson, Steve. 2006. Interagency burned area emergency stabilization & rehabilitation plan, Red Eagle Fire, watershed resource assessment, hydrology and soils. 24 p.

A USGS method based on Parrett and Johnson (2004) was used to estimate design discharges for selected drainages (table 38). To estimate the potential watershed response from these areas, a *modifier* (flow increase factor) was applied to the USGS predicted pre-fire flow values. The percent of the basin that had either high or moderate burn severity was used as the modifier (e.g., 48.6% of high and moderate burn severity = 1.486 for modifier). The modifier was applied to events with return intervals of 25 year or less.

[Table 38. Predicted pre- and post-fire flows based on Parrett and Johnson (2004) for the 2006 Red Eagle Fire, Montana (Sirucek and others, 2006).]

Story, Mark. 2003. [E-mail circulation]. September. Stormflow methods.

For larger watersheds (greater than 5–10 mi^2), CN methods are not appropriate since uniform rainfall distribution within the entire watershed usually results in overestimation of the peak flow. For larger watersheds, the USGS regression equations by Omang (1992) can be used to estimate the pre-fire peak flow. The post-fire peak flow is then approximated by assumptions about post-fire water yield increase. On the Skalkaho/Valley Complex Fires in the Bitterroot National Forest in 2000, it was assumed that high burn severity areas had 1/3 and 1/6 soil water repellencies with a 10 times increase in surface runoff at the same year and one year after the fire. This procedure can be much more accurate if burned sites are located near gaged sites on the same stream, and gaged data is used to estimate pre-fire peak flow. This procedure is also most applicable to longer duration precipitation events and snowmelt runoff events.

Story, Mark; Johnson, Steve; Stuart, Bo; Hickenbottom, Jennifer; Thatcher, Ron; Swartz, Scott. 2006. BAER specialist report, hydrology and roads, Derby Fire. 17 p.

The Derby Fire burned 223,570 acres on the Gallatin and Custer National Forest in Montana in 2006. Stormflow response recovery is related to the reestablishment of grass/shrubs and on the Gallatin NF typically takes 1–5 years depending on the burn severity. On the Gallatin NF, most of post-fire peak flow increase was observed up to two years after the wildfires (Thompson Creek Fire, 2000; Fridley Fire, 2002). The USGS regression equations from Parrett and Johnson (2004) were adjusted to analyze the potential post-fire flooding caused by the Derby Fires for watersheds greater than 5,000 acres. Pre-fire runoff was modified to estimate to post-fire runoff using *modifier* that was defined as a ratio of post-fire to pre-fire runoff. Since a 100 % peak flow increase was assumed for high and moderate burn severity area, the modifier was 100% plus the percent of the watershed that was categorized into high and moderate burn severity area. For example, if high and moderate burn severity was 45%, then the modifier was 1.45. Table 39 shows how to calculate post-fire peak flow using modifier.

[Table 39. USGS regression method to calculate post-fire peak flow for large watersheds (> 5,000 ac) burned by the 2006 Derby Fire, Montana (Story and others, 2006).]

Dixon, Mike. 2008. [Personal note]. March 17. 100 year flood flow culvert analysis.

[Table 40. Culvert analysis for 100 year flood flow for Payette National Forest, Idaho using USGS regression method (Dixon, 2008).]

3.6.2 Curve Number Methods

Gerhardt, Nick. 2006a. [Unpublished report]. June 26. NRCS post-fire stormflow model, step-by-step.

FIRE HYDRO (figures 9 to 11), an Excel spreadsheet, was developed in 2001 by NRCS in Montana for use in post-fire stormflow runoff precipitation (Cerrelli, 2005) using CN methods (USDA SCS, 1972; USDA SCS, 1991). Following steps were suggested to use FIREHYDRO.

1. Determine if this is an appropriate model to use
2. Calculate watershed area (acres)
3. Calculate mean watershed slope
4. Calculate pre-fire composite runoff curve number
5. Calculate post-fire composite runoff curve numbers (year 1, 2, and 3)
6. Look up precipitation input values from NOAA Atlas 2 (Miller and others, 1973)
7. Determine storm type and unit peak flow (from nomographs)
8. Compare results to unit area measured values (Parrett and others, 2004)
9. Rerun if necessary
10. Interpret results

Gerhardt, Nick. 2006b. [Unpublished report]. December 18. Characterization of a post-fire debris flow and flood, Blackerby Fire, Idaho.

The Blackerby Fire on the Nez Perce National Forest near Grangeville, Idaho occurred in August 2005. On 19 May 2006 a 0.79 inch precipitation event with a 30 minute duration occurred over a portion of the burned area. The precipitation event was equivalent to a 25 year-30 minute storm event as determined from NOAA Atlas 2 (Table 41).

[Table 41. Local precipitation-frequency values from NOAA Atlas 2 for the 2005 Blackerby Fire, Idaho (Miller and others, 1973; Gerhardt, 2006).]

The NRCS CN flood flow model results used in the BAER analysis (using FIRE HYDRO) were for a 25-year return event and based on the assumption of limited soil and vegetation regeneration during the first year after the fire (table 42). The observed flood discharge value was 71 cfs or 56 cfsm (cfs per sq. mile). This observed flood discharge was half that of predicted flow. Additionally, the observed debris flow discharge was 620 cfs or 492 cfsm, indicating that debris flow discharge was nearly an order of magnitude greater than the flood discharge (table 43).

[Table 42. NRCS peak flow discharge model output in 2nd post-fire period, one year after the 2005 Blackerby Fire, Idaho (Gerhardt, 2006).]

[Table 43. Observed flood and debris flow on May 19, 2006,one year after the 2005 Blackerby Fire, Idaho (Gerhardt, 2006).]

Story, Mark. 2003. [E-mail circulation]. September. Stormflow methods.

For small watersheds (less than 5 mi^2), a simple DOS model developed by Hawkins and Greenberg (1990), WILDCAT4, is useful to estimate post-fire peak flow. The WILDCAT4 is a NRCS CN method program, and allows the user to use from a 15 minute to a 24 hour storm. A CN of 90–95 is appropriate for high severity burn without water repellent soils and a CN of 93–98 is appropriate for high severity and with water repellent soils.

The WILDCAT4 uses a weighted average CN for a watershed for a watershed (e-mail circulation, Story, 2003) [*Hawkins (personal communication, 2008) commented that the WILDCAT4 uses weighted runoffs.*]. The WILDCAT4 tends to have long time of concentrations (T_c). If a shorter T_c is preferred, user can substitute T_c from equation 5 (US SCS, 1972; Dunne and Leopold, 1978), which will generate a higher peak flow due to a quicker watershed response to the storm events.

$$T_c = \frac{L^{1.15}}{7700 \cdot H^{0.38}} \qquad \text{(Equation 5)}$$

where

T_c = time of concentration (hr);
L = length of the catchment along the mainstream from the basin outlet to the most distant ridge (ft); and,
H = difference in elevation between the basin outlet and the most distant ridge (ft).

Storm distributions can be customized into WILDCAT4 program using Arkell and Richards (1986).

For watersheds up to 5 mi^2 (often 10 mi^2), a NRCS CN method using an Excel spreadsheet, FIRE HYDRO (Cerrelli, 2005) is useful for estimating post-fire peak flow in Montana. The FIRE HYDRO is applicable for 24 hour rainfall events only, and not applicable for short duration rainfall events such as one hour storm or less. Use of FIRE HYDRO for short duration events may result in underestimation of the peak flow.

Stuart, Bo. 2000. Maudlow Fire, Burned Area Emergency Rehabilitation (BAER) plan. Townsend, MT: U.S. Department of Agriculture, Forest Service, Northern Region, Helena National Forest.

Snowmelt runoff does not provide peak flow events in the fire area. During June to early September, convective rainstorms have moderate intensity over the fire area. Monsoon type rainfall events in spring and summer pose greatest risk to the watersheds of concern. The NOAA Atlas 2 (Miller and others, 1973) indicated 1.6, 2.0, and 2.4 inches of rainfall for 2, 5, and 10 year, 24 hour storms for the Maudlow Fire area. In order to estimate storm event peak flow, a NRCS CN method, FIRE HYDRO (Cerrelli, 2005) was used. The SCS Type I rainfall distribution curve (figure 4) was assumed for unit peak flows.

GIS was used to generate watershed acreage, burn severity acres by watershed, and watershed slopes for FIRE HYDRO. Based on observations of unburned conditions, land type/cover type, burn intensity, and water repellency conditions, the CN ranged from 60–64 for unburned areas, 70–72 for low burn severity, and 80 for moderate burn severity. There was no high burn severity area in the Maudlow Fire area. Potential peak flow reduction with BAER treatments was modeled by assuming the combination of seeding, contour-felling, fencing, and road drainage would reduce CN of moderate burn severity area to CN 75 and low burn severity area to CN 66. Table 44 shows the results from NRCS, FIRE HYDRO, ranging from 66 cfs in Timber Gulch to 532 cfs in Dry Creek.

[Table 44. Estimated post-fire time of concentration (T_c) and peak flows for 10 year, 24 hour storm (Q_{10}) using FIRE HYDRO (Cerrelli, 2005) for the 2000 Maudlow Fire, Montana (Stuart, 2000).]

Higginson, Brad; Jarnecke, Jeremy. 2007. Salt Creek BAER—2007 Burned Area Emergency Response. Provo, UT: Unita National Forest; hydrology specialist report. 11 p.

The WILDCAT4 (Hawkins and Greenberg, 1990) was used to estimate pre-and post-fire runoff on the 2007 Salt Creek Fire, Utah. Approximately 21,996 acres (34.4 mi^2) were burned within the fire parameters whereas 2,663 acres (4.2 mi^2) were unburned. Approximately 22% and 64% of the burned area had high and moderate severity burn. The selected watersheds (0.7–4.0 mi^2) were modeled for pre-and post-fire peak flow.

Annual precipitation mainly consists of winter snowfall and spring rainfall; however, short-duration, high-intensity summer/fall thunderstorms often produce flash flooding in the area. Thunderstorms during the fire caused flooding within the area on 7/25/2007 and 7/27/2007. To estimate pre-and post-fire peak flow, the 10-year and 25-year, 30 minute storms were used: 0.77 inch and 1.0 inch from NOAA Atlas 14 (Bonnin and others, 2006). To estimate pre- and post-fire peak flow, the following assumptions were made:

- The storm was distributed over the entire watershed.
- SCS Type II rainfall distribution (figure 4).
- The pre-fire CNs were obtained from soil surveys. Otherwise, CNs were based on vegetation type with (1) hydrologic soil group D (table 13), (2) hydrologic condition between good and fair, and (3) tables in US SCS (1991).
- Post-fire CNs were based on pre-fire CNs and burn severities :

    1. High burn severity CN = pre-fire CN + 15
    2. Moderate burn severity CN = pre-fire CN + 10
    3. Low burn severity CN = pre-fire CN + 5
    4. Maximum CN value is 100.

- Time of concentration was based on equation 5 (US SCS, 1972; Dunne and Leopold, 1978)

Table 45 and 46 show dramatic increase in calculated peak flows in drainages with moderate and high burn severities for the five selected watersheds. Use of the 25-year storm produced very high peak flow that was beyond the treatable range; therefore, 10-year storm was chosen for design storm.

[Table 45. Pre- and post-fire modeling results for the selected watersheds for 10-year, 30 minute storm (0.77 inch) on the 2007 Salt Creek Fire, Utah, using the WILDCAT4 (Hawkins and Greenberg, 1990) (Higginson and Jarnecke, 2007).]
[Table 46. Pre- and post-fire modeling results for the selected watersheds for 25-year, 30 minute storm (1.0 inch) on the 2007 Salt Creek Fire, Utah, using the WILDCAT4 (Hawkins and Greenberg, 1990) (Higginson and Jarnecke, 2007).]

Approximately 0.5 inch of rainfall was received during the fire on July 25, 2007. The storm caused flooding in the Serviceberry Hollow and Water Hollow drainages. Observed flows were estimated as follow:

- Serviceberry Hollow – Flow was approximately 25 ft wide by average depth of 2.5 ft. Assuming a conservative velocity of 5 ft sec^{-1}, the estimated discharged was 313 cfs.
- Water Hollow - Flow was approximately 11 ft wide by average depth of 3 ft. Assuming a conservative velocity of 5 ft sec^{-1}, the estimated discharged was 165 cfs.

These estimated values correlated well with the modeling results.

Kuyumajian, Greg. [Personal note]. Greg's Curve Number thoughts.

- High burn severity w/ water repellency CN = 95
- High burn severity w/o water repellency CN = 90–91
- Moderate burn severity w/ water repellency CN = 90
- Moderate burn severity w/o water repellency CN = 85
- Low burn severity CN = pre-fire CN + 5
- Straw mulch with good coverage CN = 60
- Seeding w/ LEBs—one year after fire CN = 75
- LEBs w/o water repellency CN = 85

U.S. Forest Service Coronado National Forest. 2003. Aspen Fire, Coronado National Forest, BAER hydrology report. Tucson, AZ: U.S. Department of Agriculture, Forest Service, Southwestern Region, Coronado National Forest: 24–30.

The WILDCAT4 (Hawkins and Greenberg, 1990) was used to estimate peak flow runoff in key watersheds under pre-and post-fire conditions on the 2003 Aspen Fire, Arizona. Limited sampling of water repellency conditions indicated moderate water repellency occurred on severely burned soils. Therefore, all severely burned soils had moderately water repellency.

[Table 47. Pre- and post-fire Curve Number for the 2003 Aspen Fire, Arizona (U.S. Forest Service Coronado National Forest. 2003).]

Solt, Adam; Muir, Mark. 2006. Warm Fire—hydrology and watershed report. Richfield, UT: U.S. Department of Agriculture, Forest Service, Intermountain Region, Fishlake National Forest. 9 p.

The WILDCAT4 (Hawkins and Greenberg, 1990) was used to estimate pre-and post-fire runoff on the 2006 Warm Fire, Utah. The short duration, high intensity monsoonal storms can cause flash flooding and erosional events which were of greatest concerns within and downstream of the burned area. The estimated vegetation recovery for the Warm Fire was estimated as 3 years. The 10 year recurrence interval was selected for a design storm, which has a 10 % chance of occurring in any given year, and 27 % chance occurring in the next 3 years calculated using equation 6 (Gilman, 1964). Also 30 minute duration was selected to reflect the short duration, high intensity precipitation events that were common in the area.

$$P = 1 - \left[1 - \left(\frac{1}{T}\right)\right]^N \qquad \text{(Equation 6)}$$

where

P = the probability of a rainfall having a given return period (T) occurring at least once in N years.

Pre- and post-fire CNs were determined from a combination of sources, including Cerrelli (2005) and Dunne and Leopold (1978). The limestone derived soils of burned area were determined to be in hydrologic soil group D (low infiltration) and in the ponderosa pine/juniper vegetation type (table D.3). The following CNs were selected for the 2006 Warm Fire, Utah:

- Pre-fire CN = 80
- High burn severity CN = 90
- Moderate burn severity CN = 85
- Low burn severity and unburned CN = 80

3.6.3 TR-55

Lefevre, Robert; [and others]. 2002. BAER report, Bullock Fire, Coronado National Forest, Arizona. Tucson, AZ: U.S. Department of Agriculture, Forest Service, Southwestern Region, Coronado National Forest. 14 p.

The TR-55 model was used to estimate post-fire peak flows. Table 20 shows the analysis conducted. The “2 year post-fire equivalent” displays the corresponding flood level expected from a typical 2 year storm event. In other words, there is 50% chance of a storm event that might happen in any given year.

3.6.4 WEPP Model

Sirucek, Dean; Olson, Dennis; Butterfly, Henry; Johnson, Steve. 2006. Interagency burned area emergency stabilization & rehabilitation plan, Red Eagle Fire, watershed resource assessment, hydrology and soils. 24 p.

The WEPP model was run for 20 years to estimate the pre- and post-fire runoff and erosion potential. The results showed more runoff events with greater risks of flood and erosion (table 21). The WEPP model predicted dramatic increases of rainfall and snowmelt runoff events from 2 and 0 for pre-fire conditions to 79 and 14 for post-fire conditions.

3.6.5 R1/R4 Sediment Model

Story, Mark; Johnson, Steve; Stuart, Bo; Hickenbottom, Jennifer; Thatcher, Ron; Swartz, Scott. 2006. BAER specialist report, hydrology and roads, Derby Fire. 17 p.

Potential sediment increase from the 2006 Derby Fire, Montana was modeled using the R1/R4 sediment model (Cline and others, 1981). Sediment coefficient was adjusted based on existing road, timber harvest, and burn unit conditions. The R1/R4 model estimated the sediment increase much less than the WEPP model, because the R1/R4 model used sediment delivery and routing coefficients to estimate sediment levels at accounting points at or near the Gallatin NF.

3.6.6 Culvert Sizing

Cahoon, Joel. (2005, August 11—last update). *Circular Culvert Design Spreadsheet* [Online]. Available: http://www.wti.montana.edu/Documents/Reports/PDF/CMP_Hydraulics.xls [2008, July 8].

A quick and useful Excel template was developed for culvert sizing. The spreadsheet can be downloaded from the above website. The spreadsheet displays a culvert rating curve based on inlet, outlet, and head variable, and automatically adjusts flow type to entrance and exit conditions. The spreadsheet can generate rating tables and display them by adjusting variables including culvert diameter, length, and slope. The following comments should be noted:

1. The spreadsheet was developed for corrugated metal pipe culverts.
2. Prior to opening the file in Excel, go to the Tools/Add-Ins menu; select (1) Analysis ToolPak, (2) Analysis ToolPak – VBA, and (3) Solver Add-in; and update Add-Ins link. Quit Excel, re-load Excel, enable macros, and open the file.
3. The spreadsheet numbers that user adjusts are displayed in blue.
4. Simply change blue numbers, and hit “Run” to generate a new rating curve.

3.6.7 Rolling Dip/Water Bar

Furniss, Michael J. (2002—last update). ***The six-D system for effective waterbars*** **[Online]. Available: http://www.fs.fed.us/r5/baer/six-d.html [2008, July 13].**

The purpose of waterbars is to control erosion on roads, skid trails, trails, and firelines. Waterbars should break up drainage areas small enough that they can handle runoff during heavy rainfall with little or no erosion. Waterbars should also break up runoff small enough that runoff does not have enough energy to erode road surface. There are six D's to make effective waterbars.

1. *Drainage area*. When deciding where to put waterbars, estimate the drainage area. If the road or trail width is 12 feet or less, table 48 can be used. If the road or trail is wider than 12 feet, or runoff is contributed from cutslope (e.g., seepage or leaking), then adjustment should be made.
2. *Distance*. Distance is the spacing between waterbars on a road or trail. If there is runoff contribution from cutslope or small stream crossing, putting a waterbar at that location so that water can keep flowing downhill without disturbing that road or trail surface much. If the road or trail is wider than 12 feet, modify the distance in table 48 by the proportion of that wider road width to 12 feet. For example, if a road is 15 feet wide, drainage area is one quarter greater. Therefore, the distance should be one quarter less than table 48 indicates.
3. *Diagonal*. Do not oppose the flow energy. Waterbars built diagonal to the road lead the water off and work better. Also a diagonal waterbar has a gentle slope along its base; therefore, is less bumpy and easier to drive over. A simple rule is to add 5 to the road gradient and build the waterbar at that many degrees off the road centerline.
4. *Divert*. A good waterbar should convey the water off the road or trail. It should be deep enough to handle the flow, and at the same time, durable to withstand traffic for a certain amount of time. Excavation is much more effective than fill-in to make durable and effective waterbars.
5. *Discharge*. A good waterbar should discharge the flow. If it blocks the flow, or is a dam, the waterbar will likely fail. It should have an open outlet.
6. *Dissipate*. A good waterbar should dissipate the flow below the outlet to exhaust its erosive energy and let the water infiltrate into the soil. Slash, rock, or debris are often placed below the outlet. Enough buffer distance is also considered.

[Table 48. Recommended maximum spacing for waterbars on temporary roads, trails, skid trails, and firelines (Furniss, 2002).]

3.6.8 Culvert Survey for Treatment Assessment

Sirucek, Dean; Olson, Dennis; Butterfly, Henry; Johnson, Steve. 2006. Interagency burned area emergency stabilization & rehabilitation plan, Red Eagle Fire, watershed resource assessment, hydrology and soils. 24 p.

A field review of stream crossing/culverts was conducted on the roads within the 2006 Red Eagle Fire, Montana. The existing conditions were described for each culvert installation to assess the potential impact of post-fire peak flow to each site. Table 49 shows culvert survey information and road treatment recommendations.

[Table 49. Summary information for culverts affected by the 2006 Red Eagle Fire, Montana (Sirucek and others, 2006).]

Stuart, Bo. 2000. Maudlow Fire, Burned Area Emergency Rehabilitation (BAER) plan. Townsend, MT: U.S. Department of Agriculture, Forest Service, Northern Region, Helena National Forest.

A culvert survey was completed for the burned areas of Dry Creek and three affected tributaries to Deep Creek, i.e. Sulphur Bar Creek, Blacktail Creek, and Cedar Bar Creek. The purpose of this survey was to assess qualitatively erosion hazard and culvert plugging that might compound degradation of aquatic resource from damaging heavy storm/runoff events. Table 50 shows the culvert survey to assess road and drainage hazard for the Maudlow Fire, Montana in 2000.

[Table 50. Culvert survey results to assess road and drainage hazard for the 2000 Maudlow Fire, Montana (Stuart, 2000).]

3.6.9 Evaluation of Road Treatment Implementation

Johnson, Ada Suzanne. 2003. Aspen Fire 2003 treatment success monitoring report. Tucson, AZ: U.S. Department of Agriculture, Forest Service, Southwest Region, Coronado National Forest. 21 p.

The Aspen Fire burned 84,750 acres in the Coronado national Forest, Arizona in June and July, 2003. Emergency road treatments were applied to six mile of roads, and road treatments were evaluated during and upon completion by visual observation (table 51). The road treatments were successful in protecting roads and maintaining access to residences and critical communication sites, and continue to perform as expected, with the single exception of Turkey Run Road where a culvert was removed and a rolling dip was constructed.

[Table 51. Evaluation of road treatment implementation for the 2003 Aspen Fire, Arizona (Johnson, 2003).

The rolling dip failed under base-flow conditions. The natural gradient of stream bed drops 2.5 to 3 ft (0.8–0.9 m) over the width of the road crossing. The downstream side of the dip eroded and the road was very close to impassible for long wheel-base vehicles. The drainage showed little or no evidence of increased flows since the fire. Also a culvert at the mouth of the canyon was damaged. Runoff from heavy rains pushed boulders and debris across the roadway, and significantly damaged the shoulder and

integrity of the roadway downstream. Boulders and debris should be considered when assessing road treatments.

Frazier, Jim; [and others]. 2005. BAER report, Cedar Fire, Cleveland National Forest, California. San Diego, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, Cleveland National Forest. 12 p.

Road treatments were implemented after the 2003 Cedar Fire, California, including restoring drainage function, installing drainage features and gates, storm patrols and warning signs. Significant rainfall events occurred in the week of October 18, 2004, and following January and February, resulting in the 3rd wettest season on record. A road survey was conducted in February and March 2005 to assess road conditions and to review effectiveness of treatments installed in spring 2004. Loss of upslope vegetation and large precipitation events produced larger than expected runoff, resulting in culvert capacities being exceeded, erosion at structures, and headcuts and culverts being severely undercut. Table 52 shows summary of road treatments initially implemented and after the 2005 wet winter season.

[Table 52. Summary of road treatments initially implemented and after the 2005 wet winter season for the 2003 Cedar Fire, California (Frazier and others, 2005).]

From the various gray literature discussed above, we summarize the following information for BAER road treatments:

- USGS regression and NRCS Curve Number methods were mostly used to estimate post-fire peak flow. However, these methods are not well established for post-fire conditions. Many BAER team members used their own rules to use USGS regression and NRCS CN methods; therefore, there is no consistent way to estimate post-fire peak flow.
- Design tools and information for culverts and rolling dips/water bars were available. Little information was found for the other road treatments.
- Many BAER road treatments for individual stream crossings were prescribed based on road/culvert survey, without considering capacities of existing road structure and increased post-fire peak flow. Road/culvert survey can give the current road/culvert conditions after the fire, and help prescribe road treatments. However, road/culvert survey alone might not provide enough information to prescribe road treatments for individual stream crossings.
- Most monitoring efforts were made on hillslope treatments, and little information was available to evaluate road treatment effectiveness. The most commonly used monitoring method was visual observation.

4. Conclusion

Our analysis of Burned Area Reports, the literature, interview comments, and gray literature lead us to the following conclusions

- Post-fire road conditions should be evaluated and road treatments only implemented if the values at risk warrant the treatment.
- Road treatment implementation should be based on regional characteristics, including timing of first damaging storm and window of implementation.
- Post-fire peak flow estimation is important to select appropriate road treatments. USGS regression and NRCS Curve Number methods are mostly used.
- USGS regression and NRCS Curve Number methods are not well established for post-fire conditions. Several BAER team members use simple rules of their own.
- Rolling dip/water bar, culvert upgrading, and ditch cleaning/armoring are the most frequently used road treatments.
- Rolling dip/water bar and ditch cleaning/armoring are preferred regardless of Regions. For Region 1 and 4, culvert upgrading is preferred, especially for fish-bearing streams. For Region 3, culvert removal with road closure and warning signs are preferred.
- Little information is available to estimate flood and debris flow capacities of road treatments other than culverts and rolling dip/water bar.
- No data is available on other road treatments to estimate and evaluate their capacities (e.g., ford crossing and ditch cleaning).
- Many BAER road treatments for individual stream crossings were recommended based on road/culvert survey, without considering capacities of existing road structure and increased post-fire peak flow.
- Relatively little monitoring of BAER road treatments has been conducted. Treatment effectiveness has mostly focused on hillslope treatments such as seeding, contour-felled logs, and mulch with little information on road treatments.

5. Recommendation

Based on the findings of this study, we recommend the following to further expand our knowledge and understanding of road treatment effects in the post-fire environment:

- Post-fire peak flow estimation methods vary. Further research is needed to ensure that the BAER specialists can easily compare pre- to post-fire peak flow changes.
- There exists insufficient knowledge of the capacity of BAER road treatments to pass estimated flood and debris flows. Design tools should be developed to estimate flood and debris flow capacity of BAER road treatments (e.g., ford crossing, and ditch cleaning), so that the BAER specialists can select road treatments based on post-fire peak flow changes and the road treatment capacities.
- Insufficient data is available to evaluate road treatment effectiveness. More systematic monitoring and further research are recommended to evaluate road treatment effectiveness.

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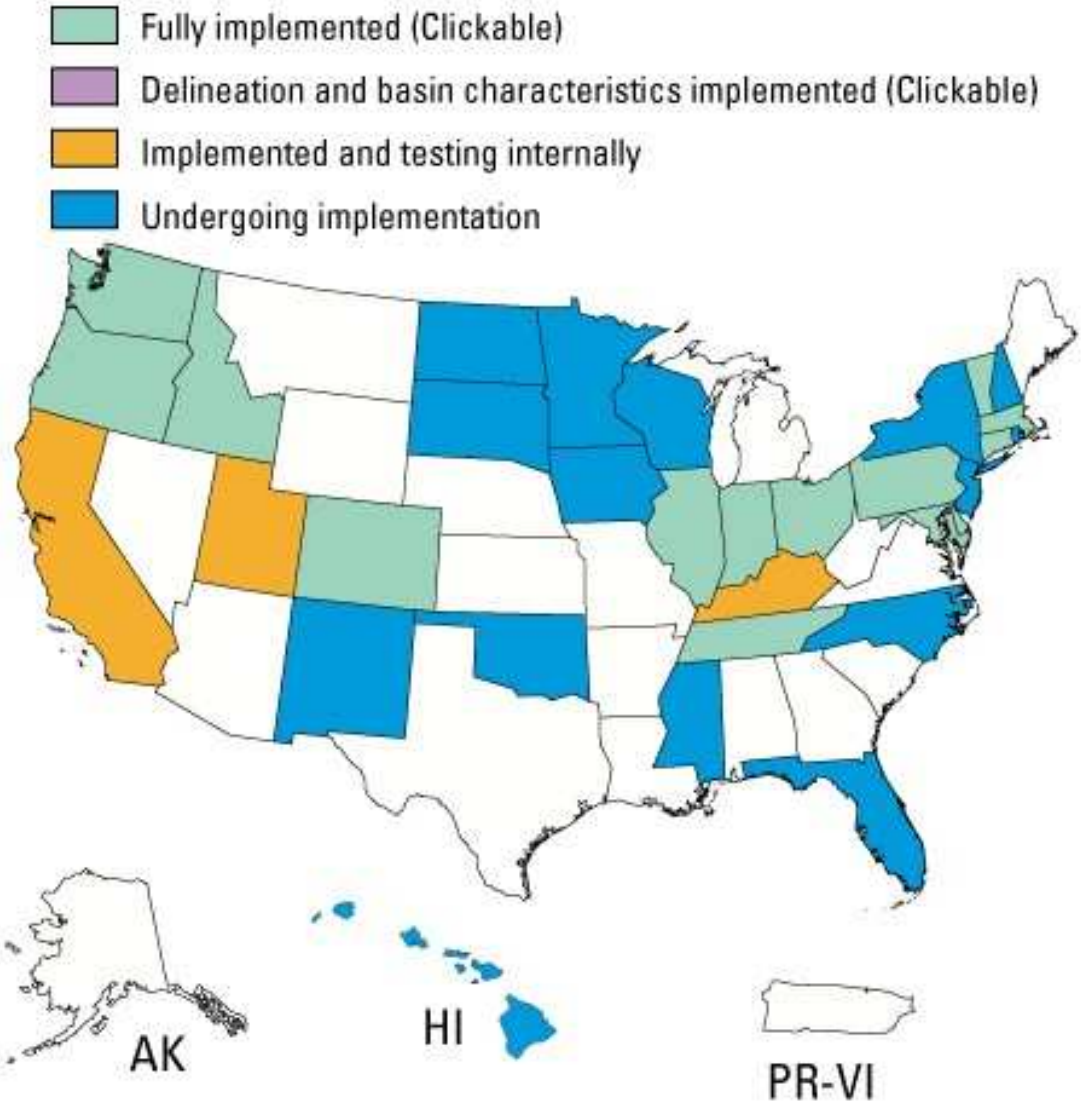


Figure 1. Availability of StreamStats for the U.S. (USGS, 2007)

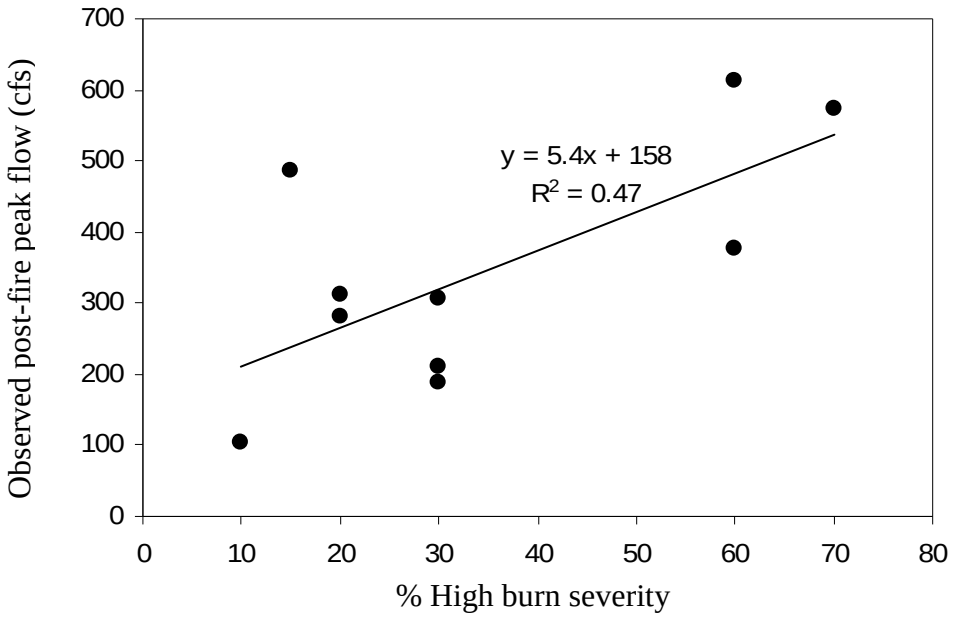


Figure 2. High burn severity area and observed post-fire peak flow (10 year-24 hour) from the 2000 Skalkaho/Valley Complex Fires in the Bitterroot National Forest, Montana (unpublished data, Story, 2002)

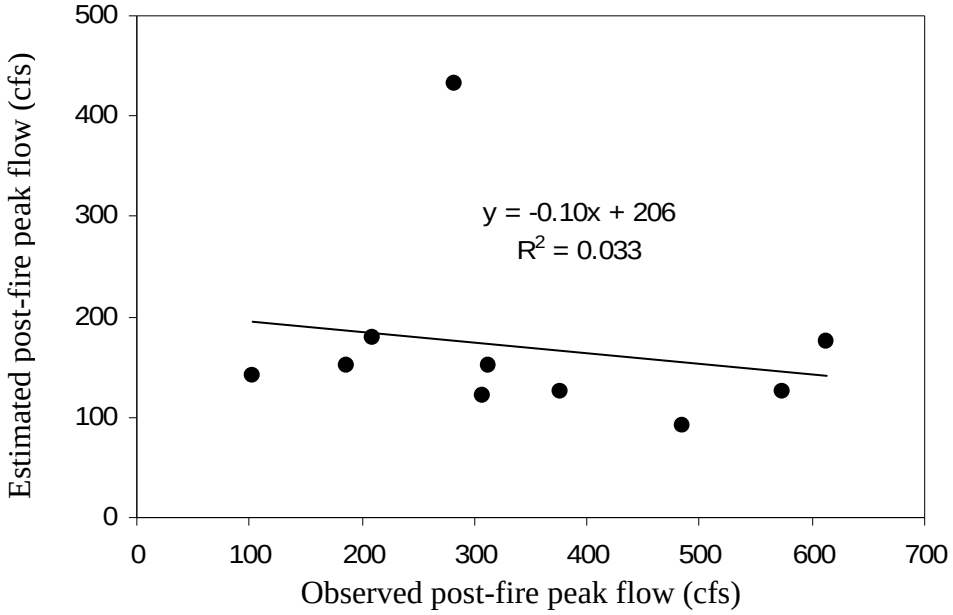


Figure 3. Observed and estimated post-fire peak flow (10 year-24 hour) from the 2000 Skalkaho/Valley Complex Fires in the Bitterroot National Forest, Montana (unpublished data, Story, 2002). Estimated post-fire peak flow does not match observed flow.

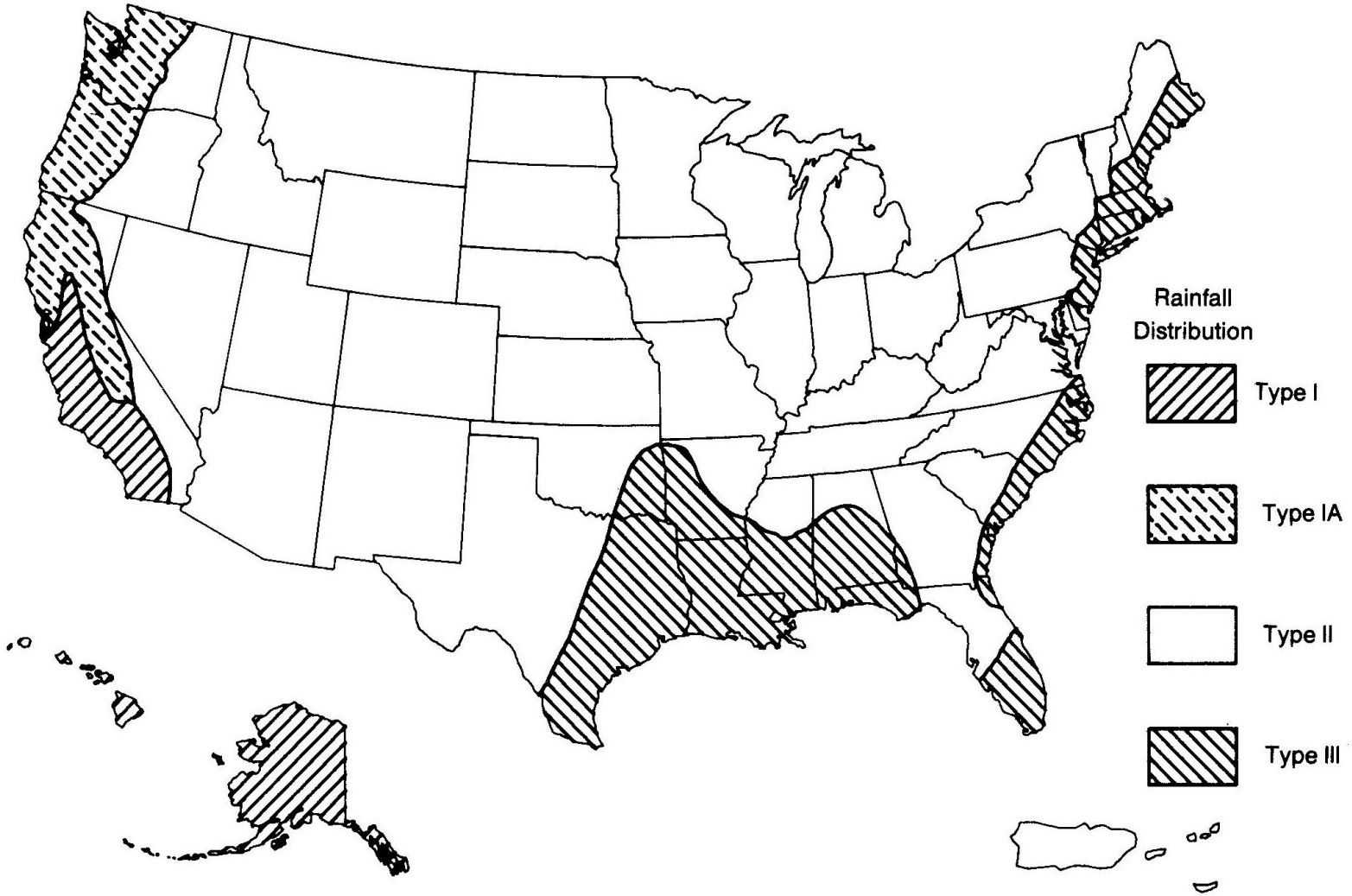


Figure 4. Approximate geographic boundaries for SCS rainfall distributions (USDA SCS, 1991)

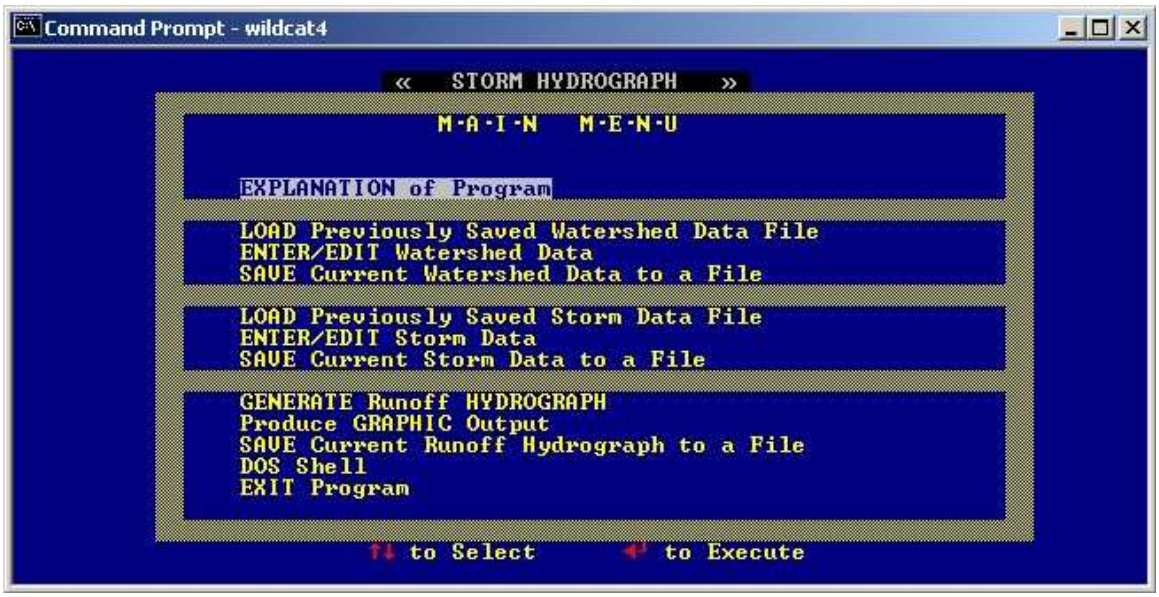


Figure 5. WILDCAT4 main menu screen

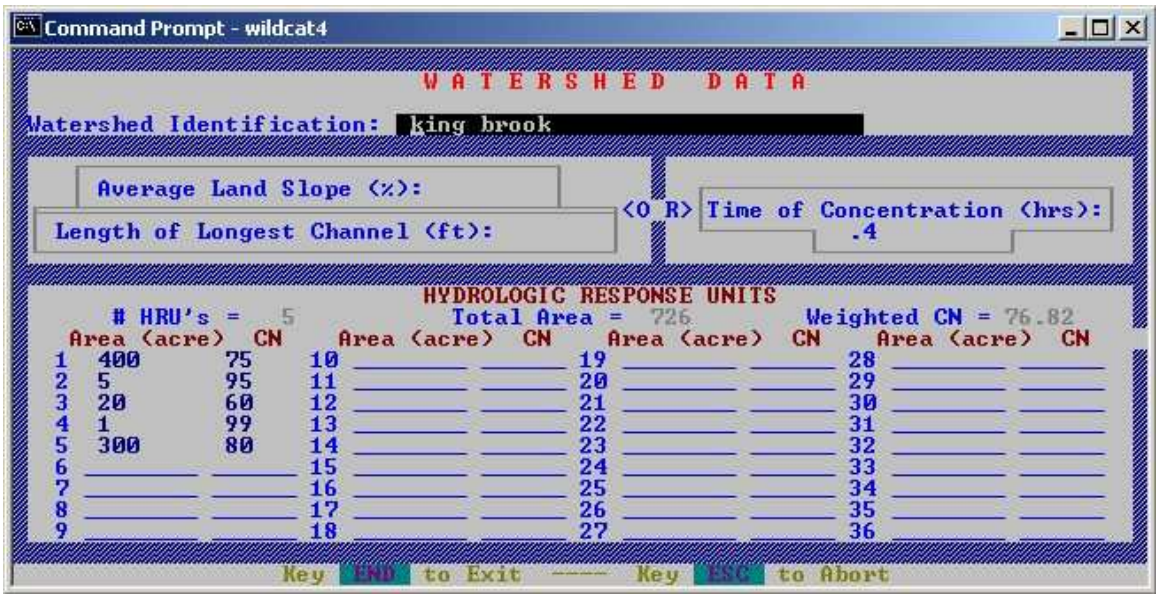


Figure 6. WILDCAT4 watershed data screen

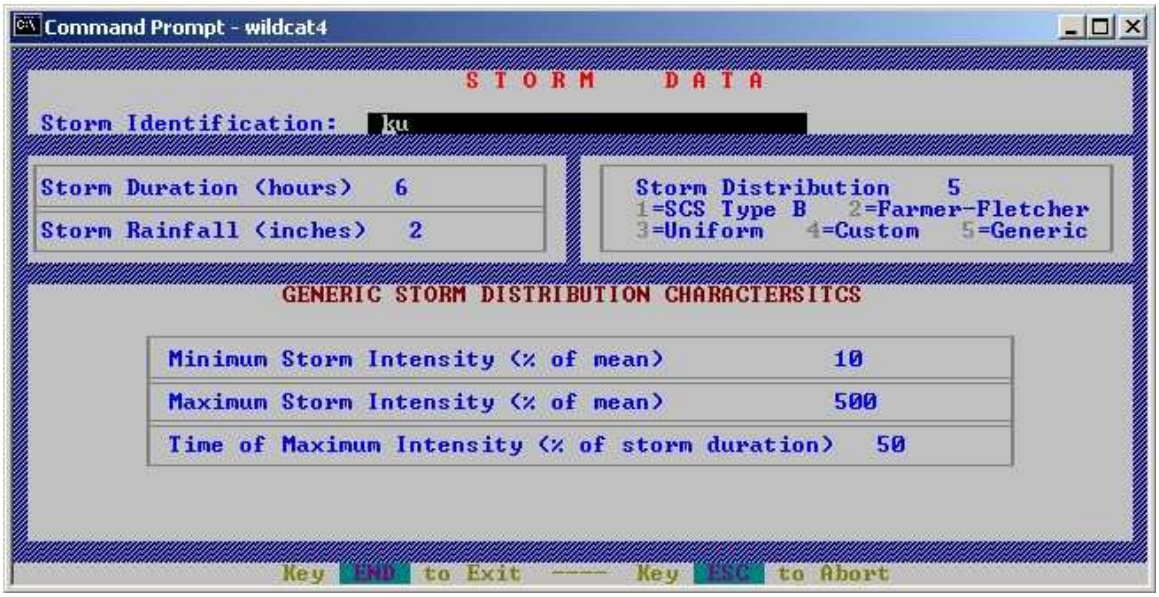
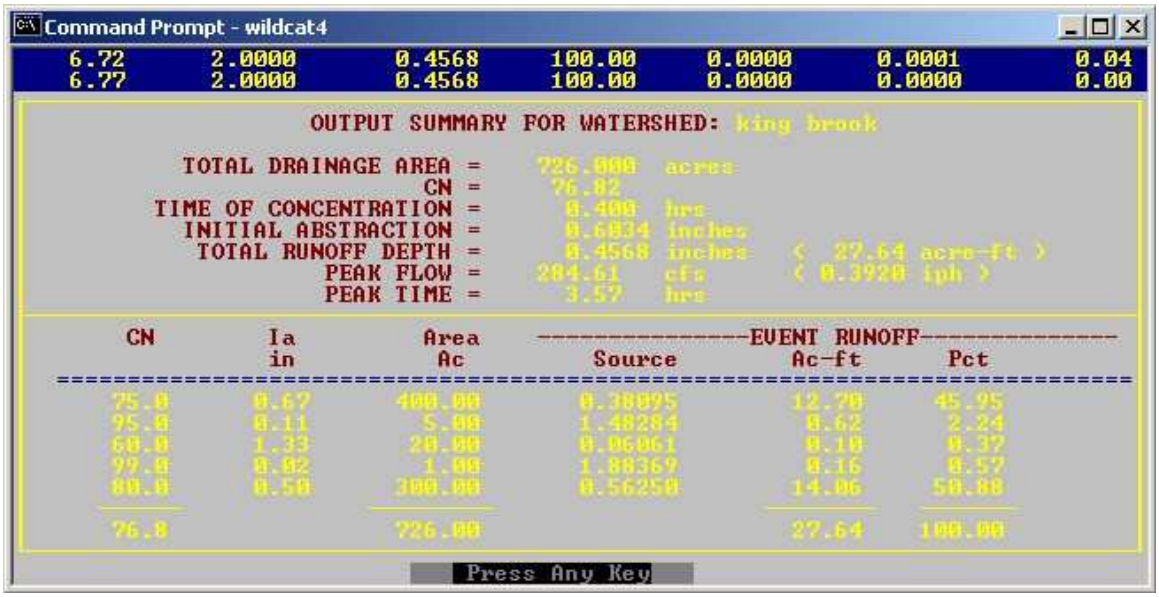


Figure 7. WILDCAT4 storm data screen



```
Command Prompt - wildcat4
6.72     2.0000     0.4568     100.00     0.0000     0.0001     0.04
6.77     2.0000     0.4568     100.00     0.0000     0.0000     0.00

                OUTPUT SUMMARY FOR WATERSHED: king brook

        TOTAL DRAINAGE AREA =    726.000  acres
                         CN =     76.82
   TIME OF CONCENTRATION =       0.400  hrs
     INITIAL ABSTRACTION =       0.6034 inches
      TOTAL RUNOFF DEPTH =       0.4568 inches   <  27.64 acre-ft >
                 PEAK FLOW =    284.61   cfs     < 0.3920 iph >
                 PEAK TIME =      3.57   hrs

     CN        Ia        Area    ----------------EVENT RUNOFF--------------
               in         Ac        Source        Ac-ft       Pct
==================================================================================
   75.0      0.67      400.00      0.38095        12.70      45.95
   95.0      0.11        5.00      1.48284         0.62       2.24
   60.0      1.33       20.00      0.06061         0.10       0.37
   99.0      0.02        1.00      1.88369         0.16       0.57
   80.0      0.50      300.00      0.56250        14.06      50.88

   76.8                726.00                     27.64     100.00

                    Press Any Key
```

Figure 8. WILDCAT 4 summary output screen

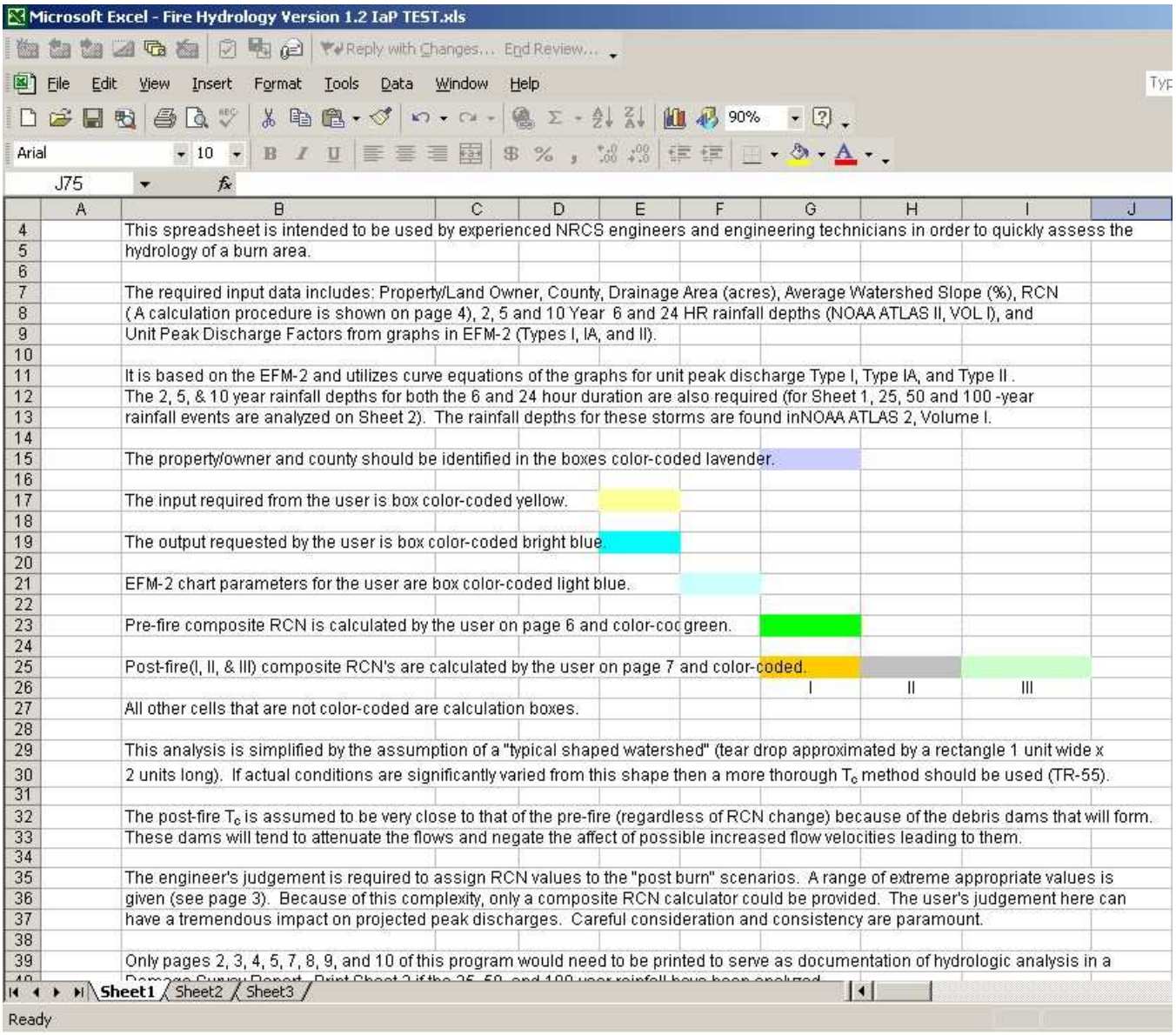
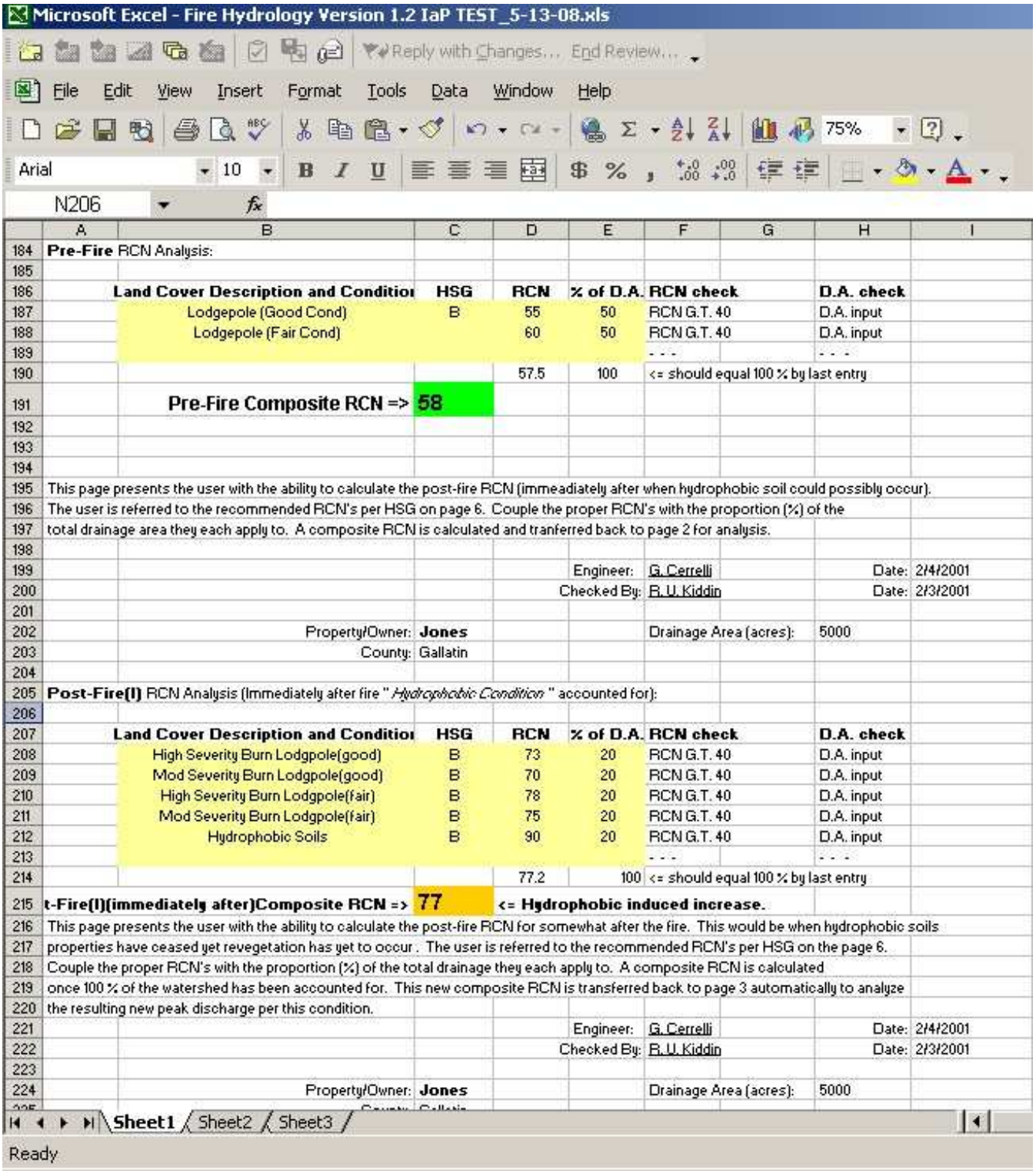


Figure 9. Explanatory section of Fire Hydro (Cerrelli, 2005), an EXCEL spreadsheet to assist to estimate peak flows for the burned areas of Montana



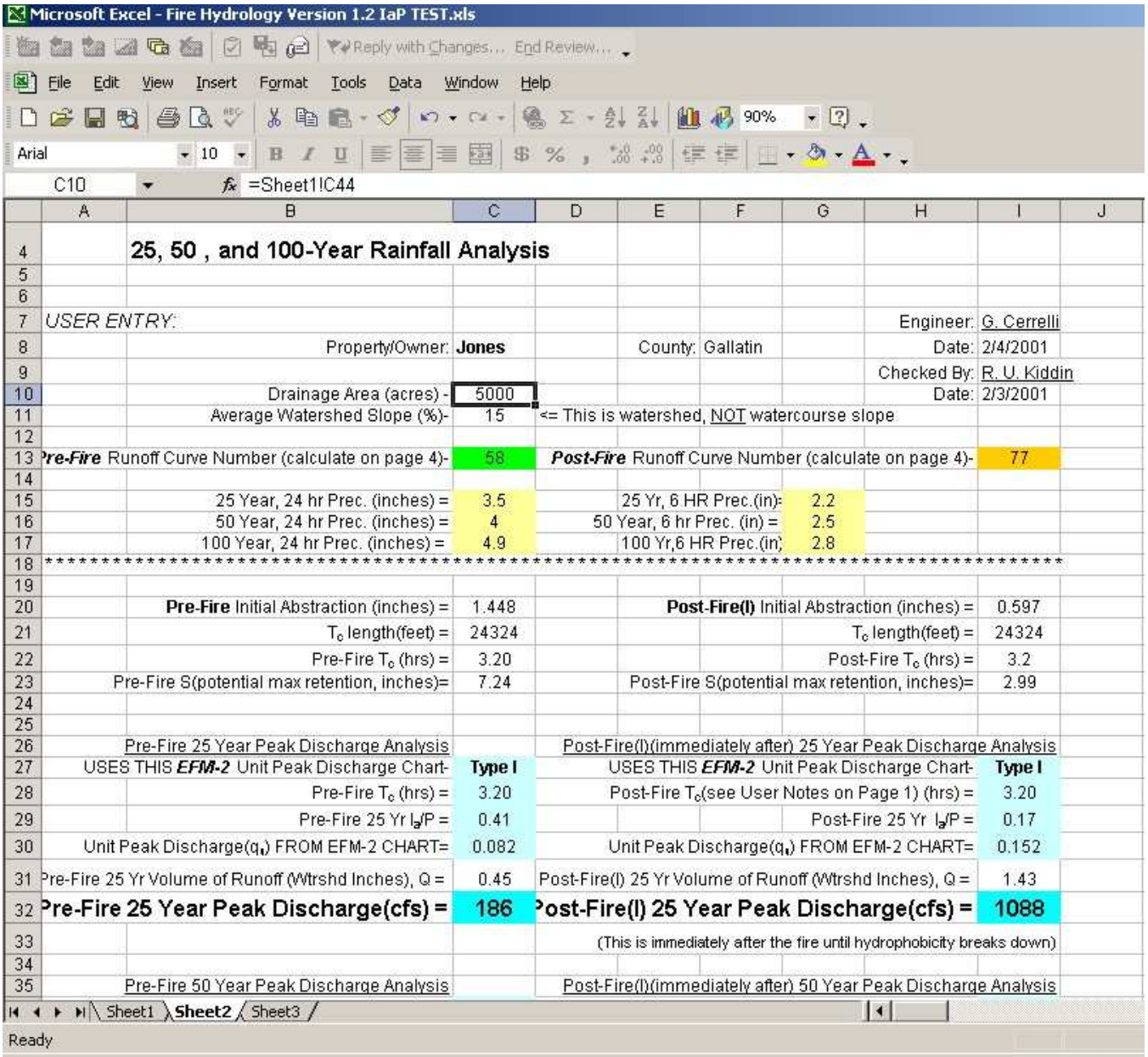
Microsoft Excel - Fire Hydrology Version 1.2 IaP TEST_5-13-08.xls

	A	B	C	D	E	F	G	H	I
184	**Pre-Fire** RCN Analysis:								
185									
186		**Land Cover Description and Conditio**	**HSG**	**RCN**	**% of D.A.**	**RCN check**		**D.A. check**	
187		Lodgepole (Good Cond)	B	55	50	RCN G.T. 40		D.A. input	
188		Lodgepole (Fair Cond)		60	50	RCN G.T. 40		D.A. input	
189						- - -		- - -	
190				57.5	100	<= should equal 100 % by last entry			
191		**Pre-Fire Composite RCN =>**	**58**						
192									
193									
194									
195	This page presents the user with the ability to calculate the post-fire RCN (immeadiately after when hydrophobic soil could possibly occur).								
196	The user is referred to the recommended RCN's per HSG on page 6. Couple the proper RCN's with the proportion (%) of the								
197	total drainage area they each apply to. A composite RCN is calculated and tranferred back to page 2 for analysis.								
198									
199					Engineer:	G. Cerrelli		Date:	2/4/2001
200					Checked By:	R. U. Kiddin		Date:	2/3/2001
201									
202		Property/Owner:	**Jones**			Drainage Area (acres):		5000	
203		County:	Gallatin						
204									
205	**Post-Fire(I)** RCN Analysis (Immediately after fire " *Hydrophobic Condition* " accounted for):								
206									
207		**Land Cover Description and Conditio**	**HSG**	**RCN**	**% of D.A.**	**RCN check**		**D.A. check**	
208		High Severity Burn Lodgpole(good)	B	73	20	RCN G.T. 40		D.A. input	
209		Mod Severity Burn Lodgpole(good)	B	70	20	RCN G.T. 40		D.A. input	
210		High Severity Burn Lodgpole(fair)	B	78	20	RCN G.T. 40		D.A. input	
211		Mod Severity Burn Lodgpole(fair)	B	75	20	RCN G.T. 40		D.A. input	
212		Hydrophobic Soils	B	90	20	RCN G.T. 40		D.A. input	
213						- - -		- - -	
214				77.2	100	<= should equal 100 % by last entry			
215	**t-Fire(I)(immediately after)Composite RCN =>**		**77**	**<= Hydrophobic induced increase.**					
216	This page presents the user with the ability to calculate the post-fire RCN for somewhat after the fire. This would be when hydrophobic soils								
217	properties have ceased yet revegetation has yet to occur . The user is referred to the recommended RCN's per HSG on the page 6.								
218	Couple the proper RCN's with the proportion (%) of the total drainage they each apply to. A composite RCN is calculated								
219	once 100 % of the watershed has been accounted for. This new composite RCN is transferred back to page 3 automatically to analyze								
220	the resulting new peak discharge per this condition.								
221					Engineer:	G. Cerrelli		Date:	2/4/2001
222					Checked By:	R. U. Kiddin		Date:	2/3/2001
223									
224		Property/Owner:	**Jones**			Drainage Area (acres):		5000	

Sheet1 / Sheet2 / Sheet3

Ready

Figure 10. Runoff Curve Number (CN) section of Fire Hydro (Cerrelli, 2005), an EXCEL spreadsheet to assist to estimate peak flows for the burned areas of Montana



Microsoft Excel - Fire Hydrology Version 1.2 IaP TEST.xls

C10 =Sheet1!C44

	A	B	C	D	E	F	G	H	I	J
4		**25, 50 , and 100-Year Rainfall Analysis**								
5										
6										
7	*USER ENTRY:*							Engineer:	G. Cerrelli	
8		Property/Owner:	**Jones**		County:	Gallatin		Date:	2/4/2001	
9								Checked By:	R. U. Kiddin	
10		Drainage Area (acres) -	5000					Date:	2/3/2001	
11		Average Watershed Slope (%)-	15	<= This is watershed, NOT watercourse slope						
12										
13	***Pre-Fire*** Runoff Curve Number (calculate on page 4)-		58	***Post-Fire*** Runoff Curve Number (calculate on page 4)-					77	
14										
15		25 Year, 24 hr Prec. (inches) =	3.5		25 Yr, 6 HR Prec.(in)-		2.2			
16		50 Year, 24 hr Prec. (inches) =	4		50 Year, 6 hr Prec. (in) =		2.5			
17		100 Year, 24 hr Prec. (inches) =	4.9		100 Yr,6 HR Prec.(in)		2.8			
18	**********									
19										
20		**Pre-Fire** Initial Abstraction (inches) =	1.448		**Post-Fire(I)** Initial Abstraction (inches) =				0.597	
21		T_c length(feet) =	24324				T_c length(feet) =		24324	
22		Pre-Fire T_c (hrs) =	3.20				Post-Fire T_c (hrs) =		3.2	
23		Pre-Fire S(potential max retention, inches)=	7.24		Post-Fire S(potential max retention, inches)=				2.99	
24										
25										
26		Pre-Fire 25 Year Peak Discharge Analysis			Post-Fire(I)(immediately after) 25 Year Peak Discharge Analysis					
27		USES THIS ***EFM-2*** Unit Peak Discharge Chart-	**Type I**		USES THIS ***EFM-2*** Unit Peak Discharge Chart-				**Type I**	
28		Pre-Fire T_c (hrs) =	3.20		Post-Fire T_c(see User Notes on Page 1) (hrs) =				3.20	
29		Pre-Fire 25 Yr I_a/P =	0.41				Post-Fire 25 Yr I_a/P =		0.17	
30		Unit Peak Discharge(q_u) FROM EFM-2 CHART=	0.082		Unit Peak Discharge(q_u) FROM EFM-2 CHART=				0.152	
31		Pre-Fire 25 Yr Volume of Runoff (Wtrshd Inches), Q =	0.45		Post-Fire(I) 25 Yr Volume of Runoff (Wtrshd Inches), Q =				1.43	
32		**Pre-Fire 25 Year Peak Discharge(cfs) =**	**186**		**Post-Fire(I) 25 Year Peak Discharge(cfs) =**				**1088**	
33					(This is immediately after the fire until hydrophobicity breaks down)					
34										
35		Pre-Fire 50 Year Peak Discharge Analysis			Post-Fire(I)(immediately after) 50 Year Peak Discharge Analysis					

Sheet1 Sheet2 Sheet3

Ready

Figure 11. Input and output section showing pre-fire and post-fire peak flow of FIRE HYDRO (Cerrelli, 2005), an EXCEL spreadsheet to assist to estimate peak flows for the burned areas of Montana. The 5,000 acre drainage area had a pre-fire 25 year peak flow of 186 cfs with a CN of 58 and post-fire peak flow of 1,088 cfs with a CN of 77, calculated from figure 9.

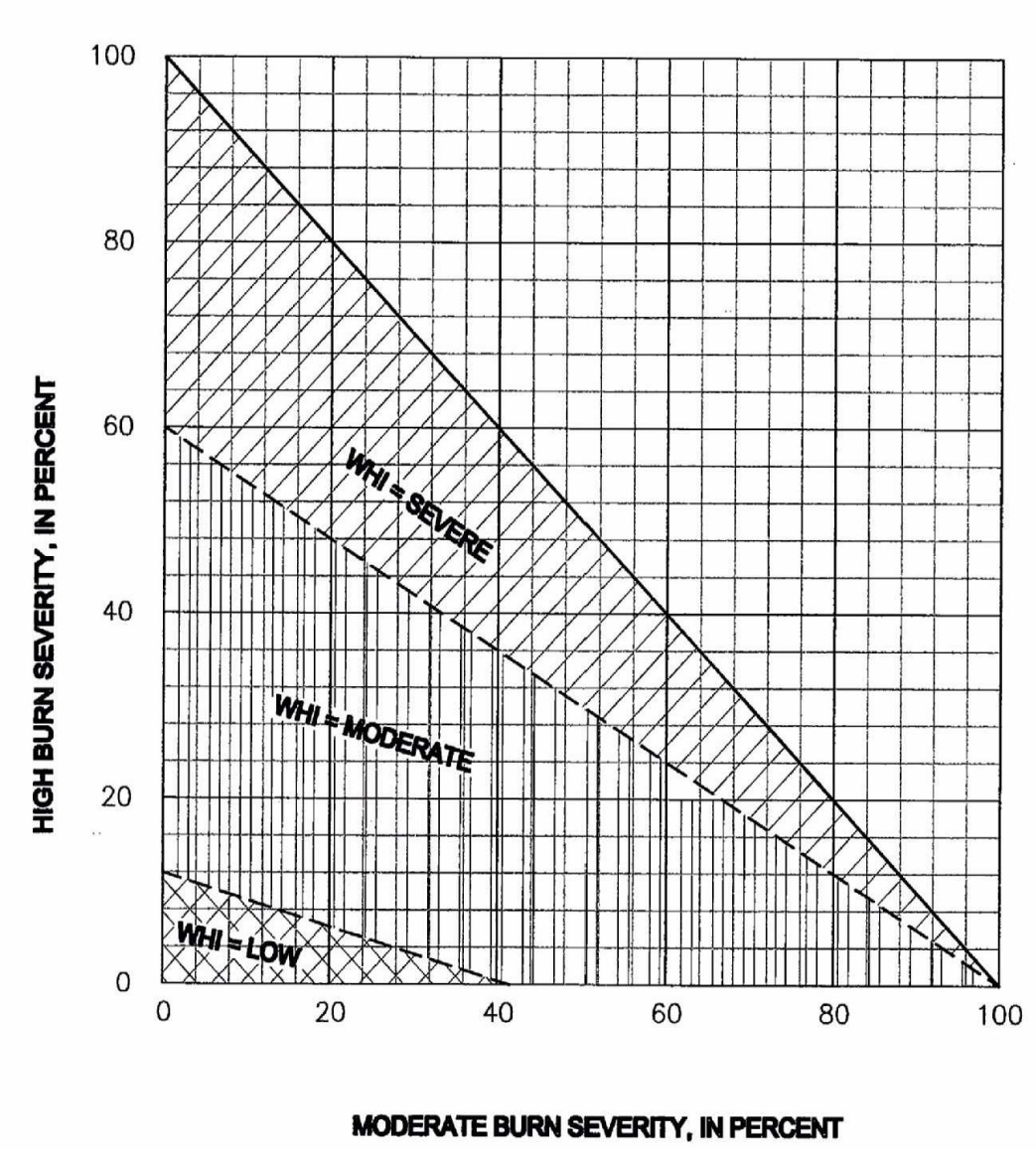


Figure 12. Wildfire Hydrologic Impact (WHI) for small burned subbasins as a function of soil burn severity (Livingston and others, 2005)

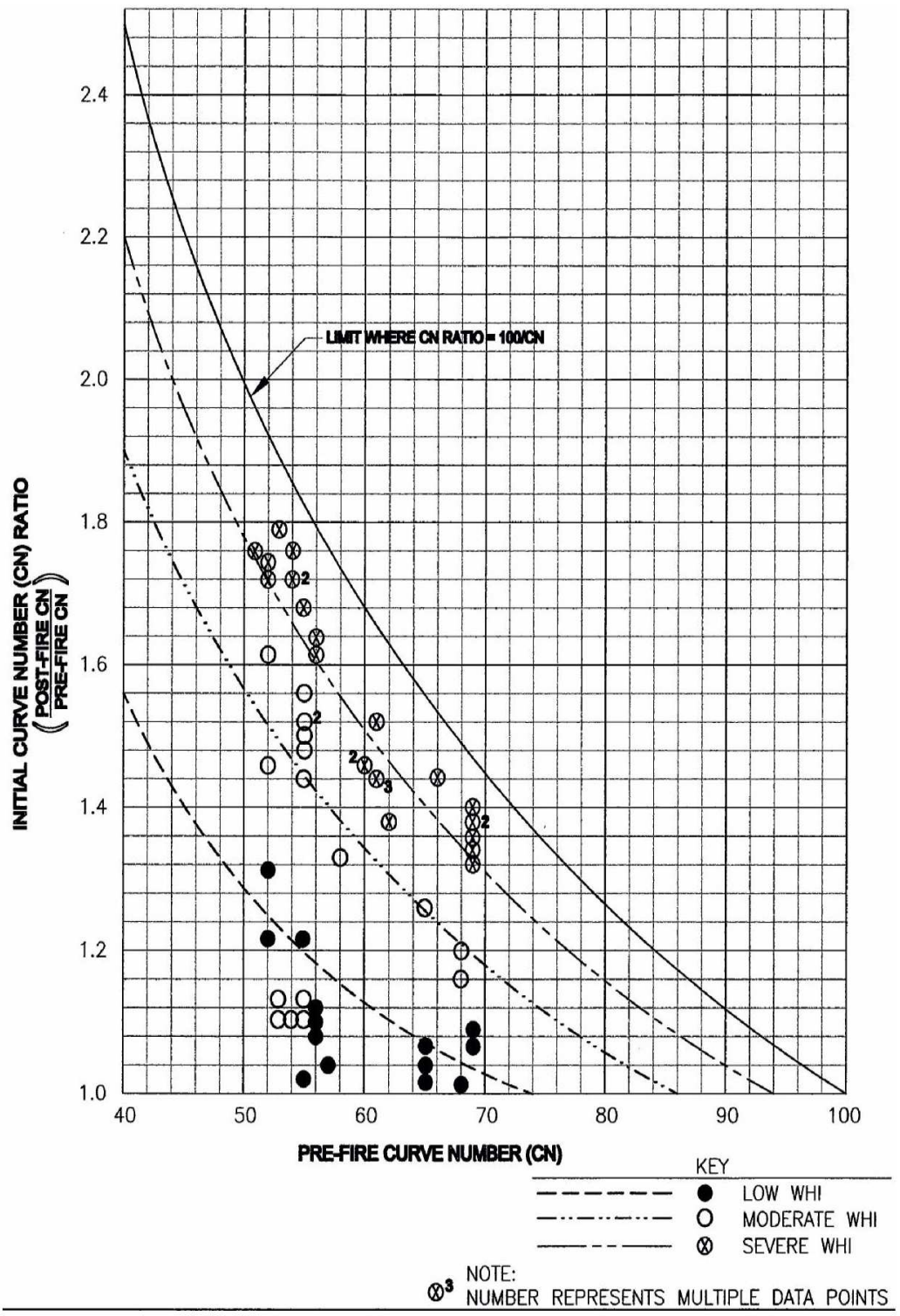


Figure 13. General relation between pre- and initial post-fire curve number (CN) ratio for indicated Wildfire Hydrologic Impact (Livingston and others, 2005)

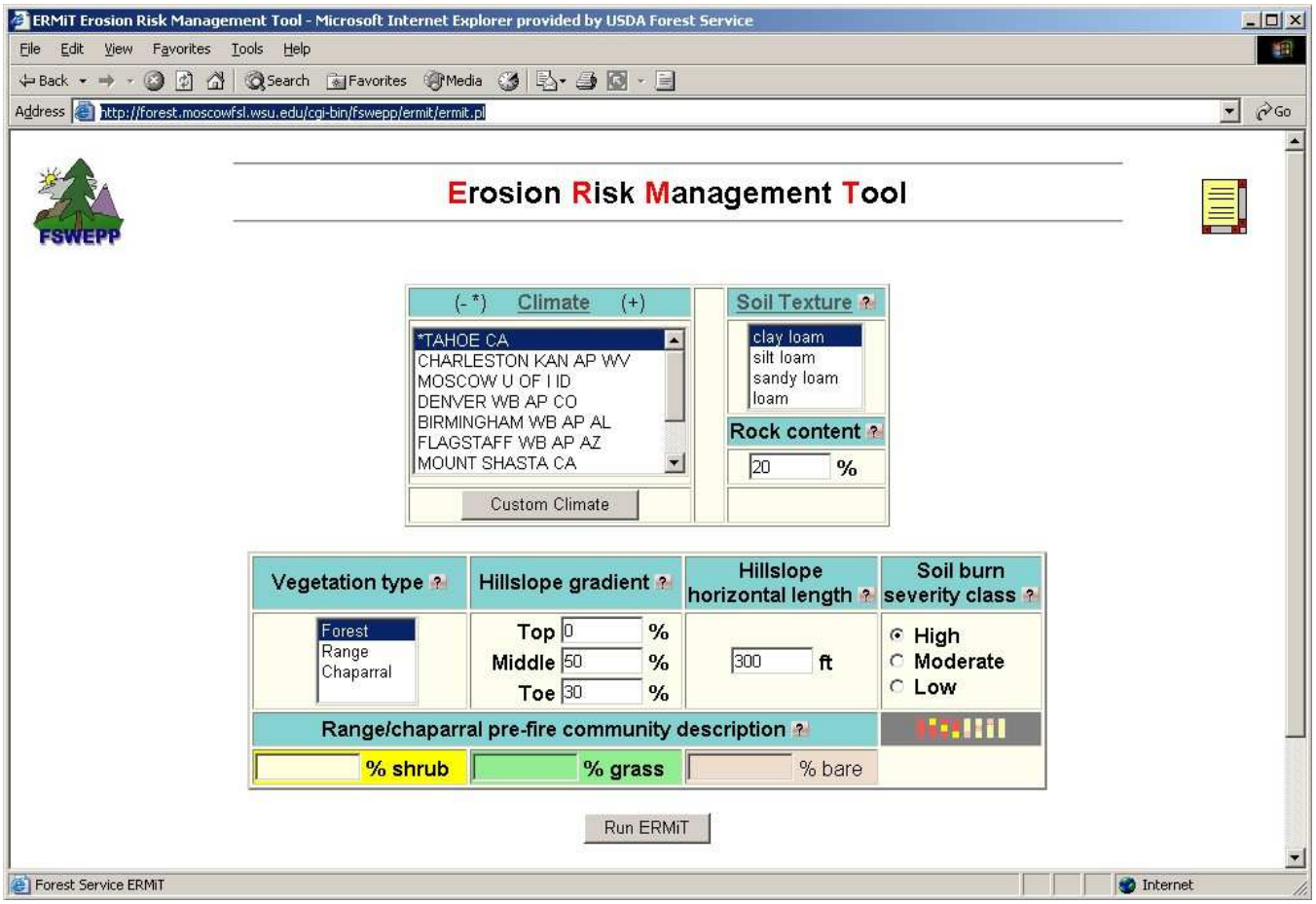
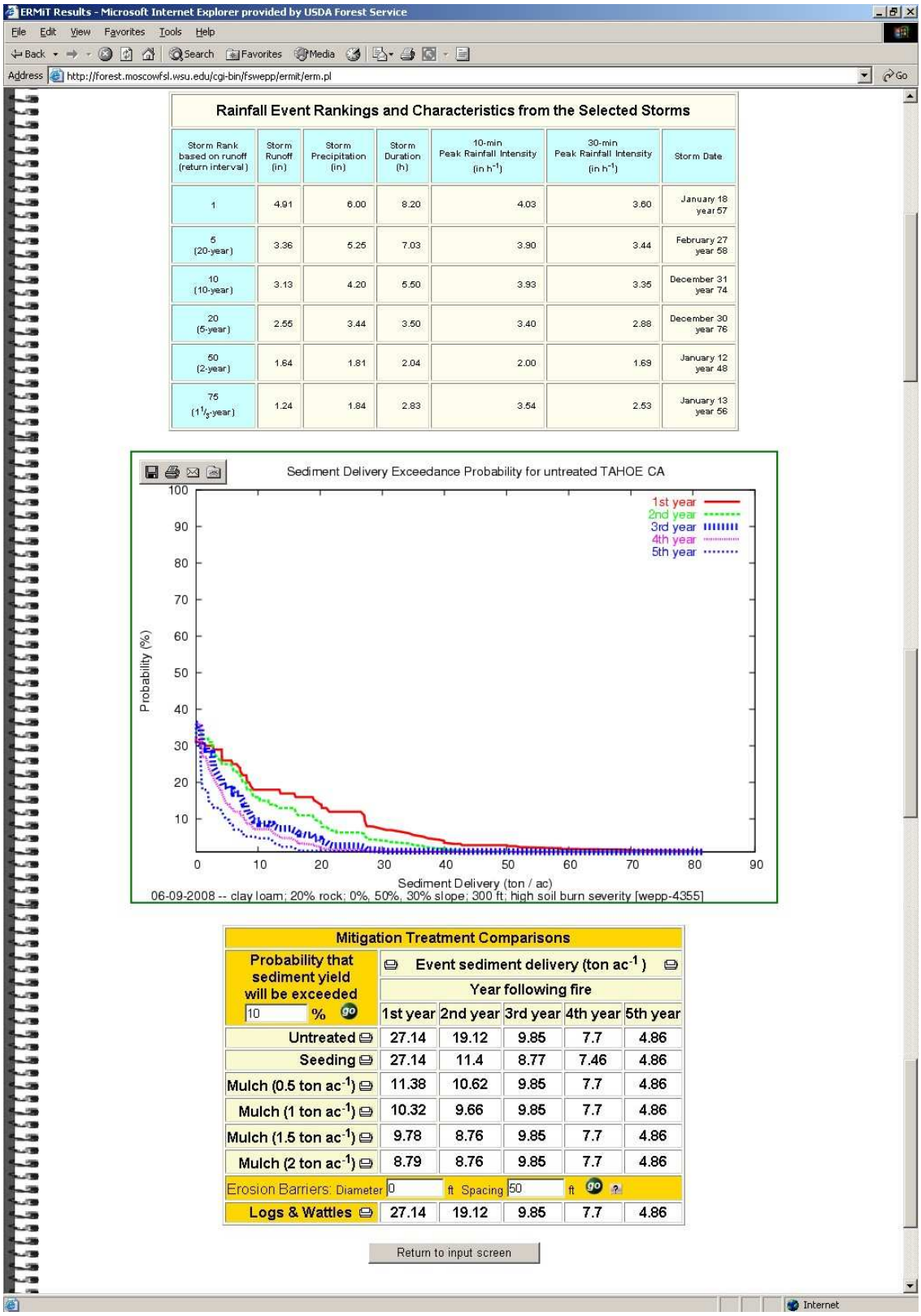


Figure 14. ERMiT input screen (http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/ermit/ermit.pl)



ERMiT Results - Microsoft Internet Explorer provided by USDA Forest Service

File Edit View Favorites Tools Help

Address http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/ermit/erm.pl

Rainfall Event Rankings and Characteristics from the Selected Storms

Storm Rank based on runoff (return interval)	Storm Runoff (in)	Storm Precipitation (in)	Storm Duration (h)	10-min Peak Rainfall Intensity (in h^{-1})	30-min Peak Rainfall Intensity (in h^{-1})	Storm Date
1	4.91	6.00	8.20	4.03	3.60	January 18 year 57
5 (20-year)	3.36	5.25	7.03	3.90	3.44	February 27 year 58
10 (10-year)	3.13	4.20	5.50	3.93	3.35	December 31 year 74
20 (5-year)	2.55	3.44	3.50	3.40	2.88	December 30 year 76
50 (2-year)	1.64	1.81	2.04	2.00	1.69	January 12 year 48
75 ($1^1/_2$-year)	1.24	1.84	2.83	3.54	2.53	January 13 year 56

Mitigation Treatment Comparisons

Probability that sediment yield will be exceeded 10 %	Event sediment delivery (ton ac^{-1}) Year following fire				
	1st year	2nd year	3rd year	4th year	5th year
Untreated	27.14	19.12	9.85	7.7	4.86
Seeding	27.14	11.4	8.77	7.46	4.86
Mulch (0.5 ton ac^{-1})	11.38	10.62	9.85	7.7	4.86
Mulch (1 ton ac^{-1})	10.32	9.66	9.85	7.7	4.86
Mulch (1.5 ton ac^{-1})	9.78	8.76	9.85	7.7	4.86
Mulch (2 ton ac^{-1})	8.79	8.76	9.85	7.7	4.86
Erosion Barriers: Diameter 0 ft Spacing 50 ft					
Logs & Wattles	27.14	19.12	9.85	7.7	4.86

Return to input screen

Internet

Figure 15. ERMiT output screen. It reports rainfall event rankings and characteristics (including runoff), the exceedance probability associated with sediment delivery, and mitigation treatment comparisons.

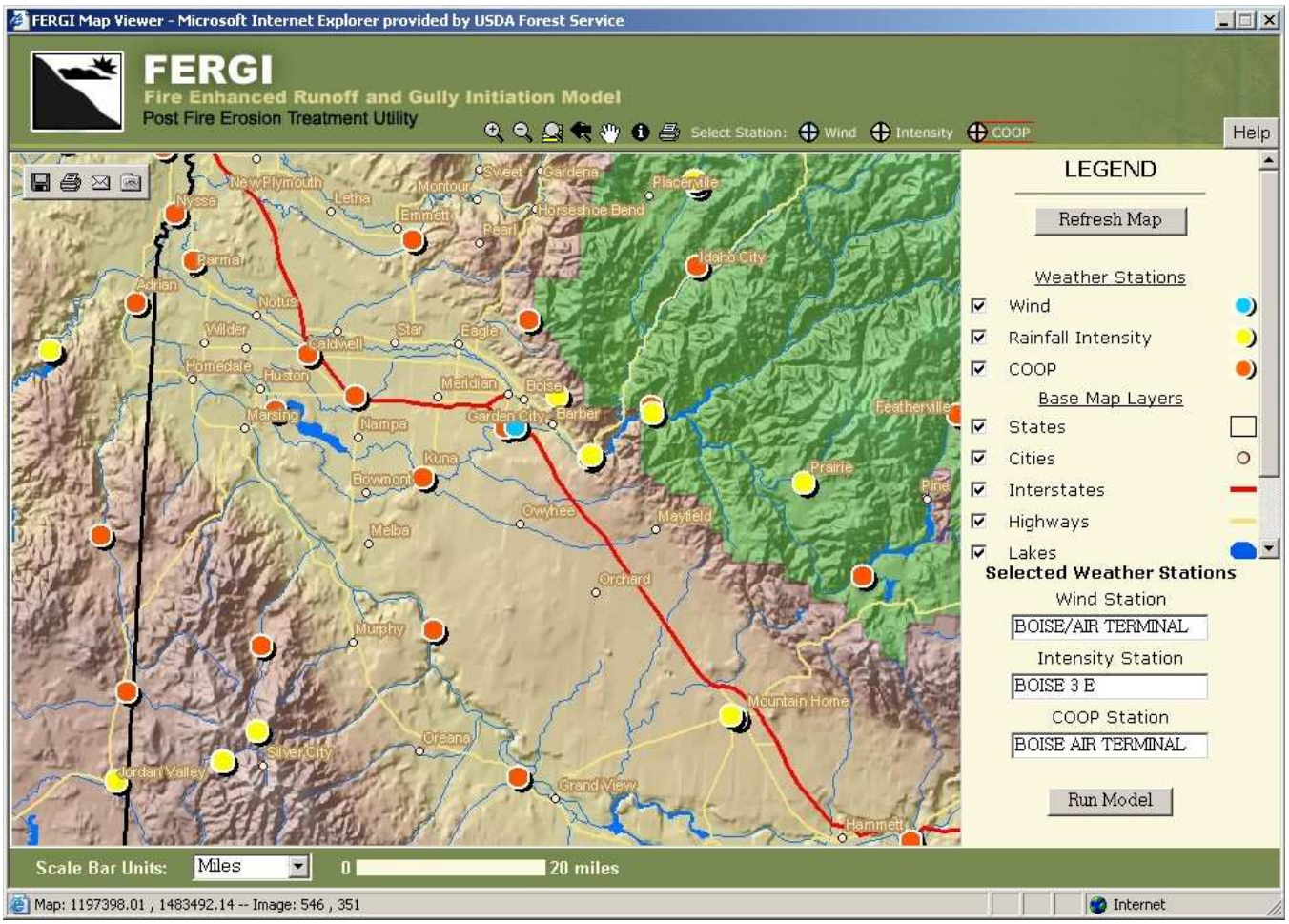


Figure 16. FERGI weather input screen

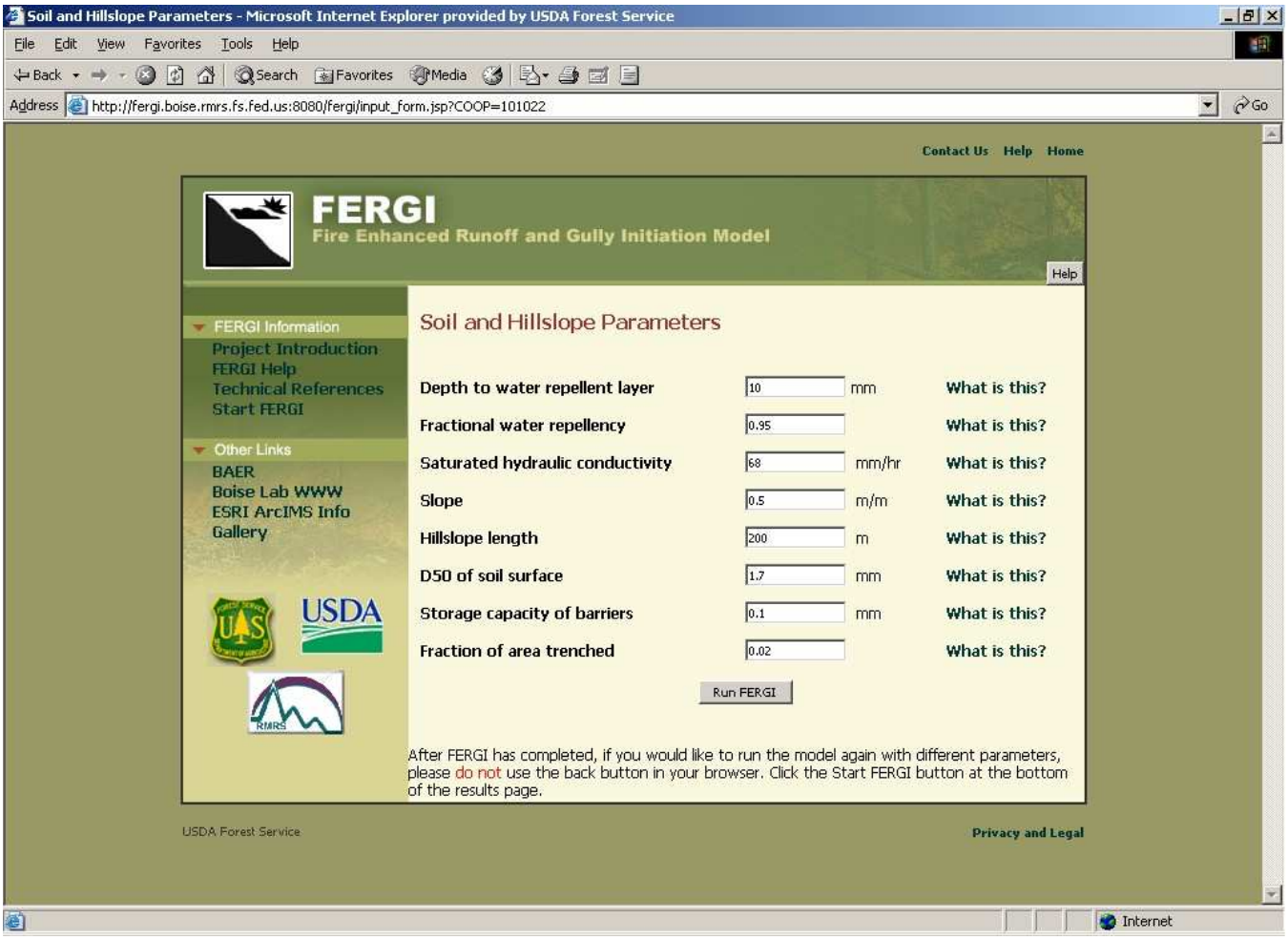


Figure 17. FERGI soil and hillslope input screen

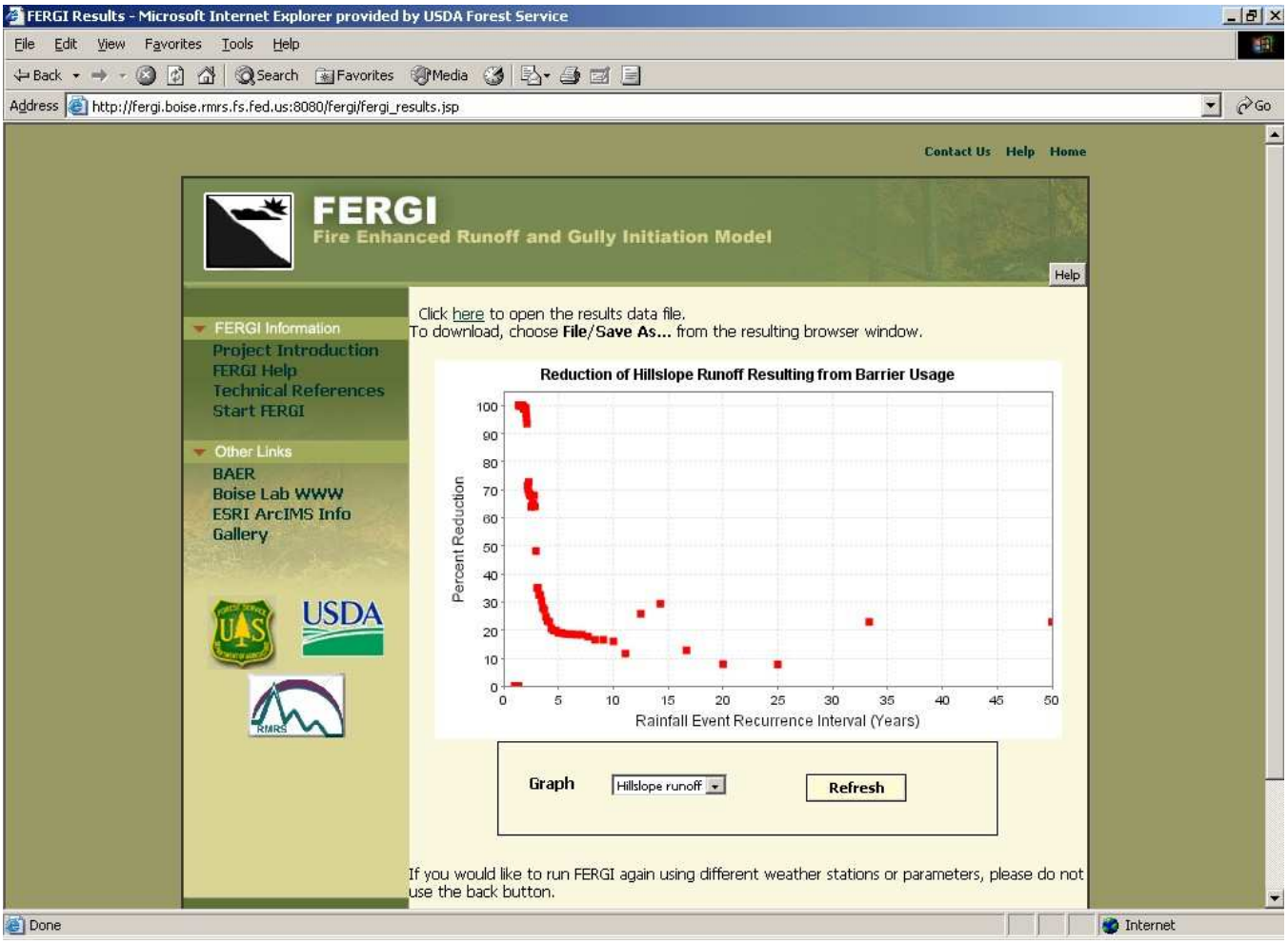


Figure 18. FERGI output as hillslope runoff graph. Usage of contour felled logs/log barrier is mostly effective for small rainfall recurrence interval (less than 5 years).

```
d2.efk_big_bear                                                                  84
corralled bear gis query, photo rd dates        061218 megfoltz
east fork big bear down to schwartz             17-06-03-06-05-15-40
 2 2007  A 19 225   5.7    4840   2760   3320   2800          50
11-A47 25   614
11-A47 30   145  EF Big Bear Creek
11-A47 40    20  EF Big Bear Creek
22-A00 25   174  EF Big Bear Creek
22-A00 30   246  EF Big Bear Creek
22-A00 40    17  EF Big Bear Creek
22-A06 25  1023  EF Big Bear Creek
22-A06 30   671  EF Big Bear Creek
22-A06 40    45  EF Big Bear Creek
22-G01 30    25  EF Big Bear Creek
22-G01 40   266  EF Big Bear Creek
22-Q01 40     0  EF Big Bear Creek
22-U25 30   226  EF Big Bear Creek
22-U25 40    60  EF Big Bear Creek
24-G10 30    65  EF Big Bear Creek
24-G10 40     0  EF Big Bear Creek
24-G20 30   193  EF Big Bear Creek
24-G20 40   162  EF Big Bear Creek
24-S10 40    40  EF Big Bear Creek
24-S20 30     1  EF Big Bear Creek
24-S20 40   256  EF Big Bear Creek
24-S25 30     1  EF Big Bear Creek
24-S25 40   219  EF Big Bear Creek
24-T11 30    50  EF Big Bear Creek
24-T25 25    18  EF Big Bear Creek
24-T25 30   508  EF Big Bear Creek
31-K10 40    95  EF Big Bear Creek
31-K20 40   208  EF Big Bear Creek
31-Q20 25     0  EF Big Bear Creek
31-Q20 30     0  EF Big Bear Creek
31-Q20 40     0  EF Big Bear Creek
31-S10 25   614  EF Big Bear Creek
31-S10 30    56  EF Big Bear Creek
31-S10 40   163  EF Big Bear Creek
31-S20 40   145  EF Big Bear Creek
31-S21 40    24  EF Big Bear Creek
31-S25 40   160  EF Big Bear Creek
31-T10 25    50  EF Big Bear Creek
31-T10 30   194  EF Big Bear Creek
31-T26 30   161  EF Big Bear Creek
31-U26 30    57  EF Big Bear Creek
31-U26 40    60  EF Big Bear Creek
61-U30 40   101  EF Big Bear Creek
63-G20 40   125  EF Big Bear Creek
99
3267  1 22-A00   .2 12 1.00 0.77    15   3190  90  90     1981        Segid 71 Rd 3267
3267  1 22-A00   .1 12 1.00 0.77    25   3290   0  90     1981        Segid 55 Rd 3267
3267  1 22-A06   .0 12 1.00 0.77     5   3060   0  90     1981        Segid 111 Rd 3267
```

Figure 19. Typical WATBAL watershed input data file format (Personal communication, Foltz, 2008). Adding input data requires understanding of the program and the natural hydrologic and erosional processes.

```
*****************************************************************************************************************************
*****************************************************************************************************************************

              **** WATBAL  (Rev. 10/2005)   Detailed Results ****               Current Date:  11/15/ 7

 Input is from Watershed file:  d2.efk_big_bear                  Tech: megfoltz                     61218
        and Alternative file:  None

           ***  Clearwater National Forest Watershed Management Guidelines  ***

  Project and Alternative:  corralled bear gis query, photo rd dates
  Watershed: east fork big bear down to schwartz                WRC: 17-06-03-06-05-15-40
  Project year:  2007                        Ranger District:   2

     Elevation(ft)  min=  2760.    max=  4840.
     Azimuth(deg)=  225       Channel length(mi)=    5.7        Hydrologic Region=  19- Potlatch River
     Geologic Subsection=  A              Channel Rating=    0

     Total Area (sq mi)=   11.34     (acres)=     7258


  Natural Watershed Condition (average annual):
    Precipitation         Runoff            Eff       Peak Runoff          Sediment Yield             Flag
     in       AF        in       AF          %      CFS-month   Days         Tons/mi/yr         Percent Increase
     31.    18911.      11.     6798.        36.        23.4     92.               18        201 ** (180 * to 231 ***)


  Altered Watershed Condition Analysis:
0**** 1950 ****
  Unit  Land   Act Road Segment  -  Slope  -  Mit Area HT Cover Elev Asp Treat Age Rec ECA  F   Runoff   Mass    Surface
        Type      Length Width  Cut Fill Side                                ment                          Incr
                     mi    ft   tan  tan   %    %   ac      %    ft  deg   %   yrs  %   ac  %     AF     tons      tons

 3347  11-A47        .1    14  1.00  .77   15   0    .2         2780 180   100   0   0   0.         .2     .00      2.16
 3347  11-A47        .2    14  1.00  .77   25   0    .5         2850 135   100   0   0   0.         .5     .00      5.02
 3347  11-A47        .2    14  1.00  .77   25   0    .5         2850 135   100   0   0   0.         .5     .00      5.02
 3347  11-A47        .3    14  1.00  .77   25   0    .7         2850 135   100   0   0   1.         .7     .00      7.53
 3347  11-A47        .0    14  1.00  .77   25   0    .0         2850   0   100   0   0   0.         .0     .00       .00
 3347  11-A47        .0    14  1.00  .77   15   0    .0         2820 180   100   0   0   0.         .0     .00       .00
```

Figure 20. Typical WATBAL watershed response summary report (Personal communication, Foltz, 2008). Interpretation of output data requires understanding of the program and the natural hydrologic and erosional processes.

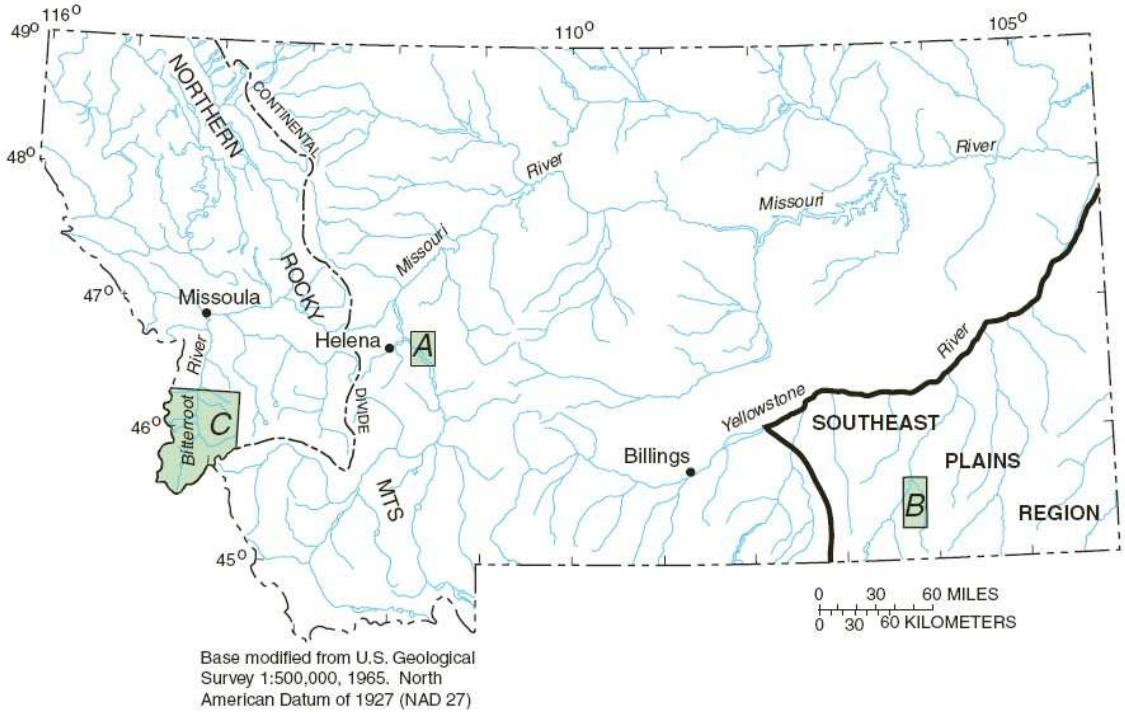


Figure 21. Location of three burned areas in Montana: A. Canyon Ferry, B. Ashland, and C. Bitterroot (Parrett and others, 2004)

Table 1. Background of interviewed BAER specialists by Regions

Background	Region						
	Overall	**1**	**2**	**3**	**4**	**5**	**6**
	Percent						
Hydrology	45	67	100	33	43	25	75
Engineering	22			17	29	38	25
Soil	20	33		17	14	25	
Natural Resource	7			17	14		
Forestry	3			17			
Road Management	3					13	
No. of BAER interviewee responses	30	6	1	6	7	8	2

Table 2. Estimated vegetation recovery period used by BAER specialists

Estimated vegetation recovery period	*Percent*
Professional judgment	42
Consult w/ botanist, ecologist, soil scientist, and hydrologist	40
Research results	8
2–3 years	8
3–5 years	3
No. of BAER interviewee responses	19

Table 3. Design chance of success used by BAER specialists

Design chance of success	*Percent*
Professional judgment	78
Consult w/ hydrologist	13
80 %	4
Stream Notes[1]	4
No. of BAER interviewee responses	23

[1] Stream Notes (October, 1998; after Schmidt, 1987) as seen in table 10.

Table 4. Equivalent design recurrence interval used by BAER specialists

Equivalent design recurrence interval	*Percent*
Consult w/ hydrologist	36
10 years	14
25 years	14
5 years	9
100 years	9
Values at risk	9
Professional judgment	9
No. of BAER interviewee responses	22

Table 5. Design storm duration used by BAER specialists

Design storm duration	*Percent*
Consult w/ hydrologist	44
1 hour	17
Depend on damaging storm	13
30 minutes	12
15 minutes	6
Less than 6 hours	4
Professional judgment	4
No. of BAER interviewee responses	23

Table 6. Design storm magnitude used by BAER specialists

Design storm magnitude	*Percent*
NOAA Atlas	46
Consult w/ hydrologist	40
PRISM[1]	8
Past experience	4
CLIGEN[2]	2
No. of BAER interviewee responses	25

[1] Daly (2007).
[2] USDA Agricultural Research Service and Forest Service (2008).

Table 7. Estimated reduction in infiltration used by BAER specialists

Estimated reduction in infiltration	*Percent*
Soil burned severity maps	46
Field measurement[1]	29
Consult w/ soil scientist	10
Previous studies	6
Back-calculation[2]	5
Professional judgment	3
40 % for high/moderate burned area	2
No. of BAER interviewee responses	22

[1] Infiltrometers were used.
[2] Back-calculate from design flow and adjusted design flow.

Table 8. Pre- and post-fire peak flow estimation methods used by BAER specialists

Pre-fire peak flow estimation method	*Percent*	**Post-fire peak flow estimation method**	*Percent*
USGS Regression	50	USGS Regression	43
Curve Number	18	Curve Number	28
Consult w/ hydrologist	18	Rule of Thumb	7
TR55	7	TR55	7
No runoff/flow	4	Consult w/ hydrologist	7
Professional judgment	4	WEPP	5
		FERGI	2
		WATBAL	2
No. of BAER interviewee responses	28	No. of BAER interviewee responses	30

Table 9. Frequently recommended road treatments by BAER specialists by Region

Method	Region						
	Overall	**1**	**2**	**3**	**4**	**5**	**6**
	Percent						
Rolling dip/water bar/cross drain	29	29		27	30	19	42
Culvert upgrading	20	33			48		17
Ditch – cleaning, armoring	16	25		14	13	17	
Culvert removal	10	6		36			25
Debris/trash rack	6			9		19	
Armored ford crossing	5		33	5	4	6	8
Culvert riser	5					19	
Storm patrol	3		50	9			
Culvert overflow bypass	2				4	6	
Hazard/warning sign	1	2	17				
Flared inlet	1					6	
Channel debris cleaning	1					6	
Culvert inlet/outlet armoring	1	2					
Additional relief culvert	1	2			3		
Outsloping road	1					3	
Fillslope armoring	1						8
No. of BAER interviewee responses	30	8	1	6	5	8	2

Table 10. Calculated risk table (recurrence interval in years) (Schmidt, 1987)

		Risk – Percent Chance																		
Success		95	90	85	80	75	70	65	**60**	55	50	45	40	35	30	25	20	15	10	5
Failure		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
Design Life (In Years)	1	20	10	7	5	4	4	3	3	3	2	2	2	2	2	2	2	2	2	2
	2	40	20	13	10	8	6	5	5	4	4	4	3	3	2	2	2	2	2	2
	3	59	29	19	14	11	9	8	7	6	5	4	4	3	3	3	2	2	2	2
	4	78	39	25	19	15	12	10	8	7	7	6	5	4	4	4	3	3	2	2
	5	98	48	32	23	18	15	13	10	9	8	7	6	6	5	4	4	3	3	2
	6	117	58	38	28	22	17	15	12	11	10	8	7	7	6	5	4	4	3	2
	7	136	67	44	32	25	20	17	14	12	11	9	8	7	6	6	5	5	4	3
	8	156	77	50	37	28	23	20	16	14	12	11	9	8	7	7	5	5	4	3
	9	175	86	56	41	32	26	22	18	16	13	12	10	9	8	7	6	5	4	4
	10	195	96	63	46	35	29	24	20	17	15	13	11	10	9	8	7	6	5	4
	11	214	104	69	50	39	31	27	22	19	16	14	13	11	10	9	7	6	5	4
	12	234	114	75	55	42	34	29	24	21	18	16	14	12	10	9	8	7	6	5
	13	254	124	81	59	46	37	31	26	22	19	17	15	13	11	10	9	7	6	5
	14	273	133	86	64	49	40	34	28	24	21	18	16	14	12	11	9	8	7	5
	15	293	143	93	68	53	43	36	30	26	22	19	17	15	13	12	10	8	7	6
	16	312	152	99	73	56	45	38	32	27	24	20	18	16	14	12	10	9	8	6
	17	332	162	105	77	60	48	40	34	29	25	22	19	17	15	13	11	9	8	6
	18	351	171	111	82	63	51	43	36	31	26	23	20	18	15	14	12	10	8	7
	19	371	181	117	86	67	54	45	38	32	28	24	21	19	16	14	12	11	9	7
	20	390	190	123	91	**70**	57	47	40	34	29	26	22	20	17	15	13	11	9	8
	25	488	238	154	113	88	71	59	50	42	36	32	28	25	22	19	16	14	11	9
	30	585	285	185	135	105	85	71	60	51	44	38	33	29	25	22	19	16	14	11
	35	683	333	216	157	122	99	82	70	59	51	45	39	34	30	26	23	19	16	12
	40	780	380	247	180	140	113	94	79	68	58	51	44	39	34	29	25	22	18	14
	45	878	428	277	202	157	127	105	89	76	66	57	50	43	38	33	28	24	20	15
	50	975	475	308	225	174	141	117	99	85	73	63	55	48	43	37	32	27	22	17
	60	1170	570	370	269	209	169	140	118	101	87	76	66	58	50	44	38	32	27	20
	70	1365	665	431	314	244	197	163	138	118	101	89	77	67	59	51	44	37	31	24
	80	1560	760	493	359	279	225	186	157	134	116	101	88	77	67	58	51	43	35	27
	90	1755	855	554	404	313	253	209	177	151	130	113	99	86	75	66	57	48	40	31
	100	1950	950	616	449	348	281	233	196	168	145	126	110	96	84	73	63	53	44	34

Example 1: If a culvert through a road is to last for 20 years with a 25% chance of failure (or 75% chance of success), the culvert should be designed for the 70-year flood recurrence event. Failure in this context means that the recurrence interval flood is equaled or exceeded at least once during the specific design life. The culvert may or may not physically fail or be washed out.

Example 2: The same culvert above is used for post-fire condition in which 7-year post-fire flood is equal to 70-year pre-fire flood. Post-fire condition will last for only 3 years; therefore, the design life will be 3 years. Then percent chance of success decreased from 75% to 60% if the existing culvert is used for post-fire condition.

Table 11. Changes in hydrologic processes caused by wildfires (Neary and others, 2005)

Hydrologic process	Type of change	Specific effect
Interception	Reduced	Moisture storage smaller Greater runoff in small storms Increased water yield
Litter and duff storage of water	Reduced	Less water stored Overland flow increased
Transpiration	Temporary elimination	Streamflow increased Soil moisture increased
Infiltration	Reduced	Overland flow increased Stormflow increased
Stream flow	Changed	Increased in most ecosystems Decreased in snow systems Decreased on fog-drip systems
Baseflow	Changed	Decreased (less infiltration) Increased (less evaporation) Summer low flows (+ and –)
Stromflow	Increased	Volume greater Peakflows larger Time to peakflow shorter Flashflood frequency greater Flood levels higher Stream erosive power increased
Snow accumulation	Changed	Fires < 10 ac, increased snowpack Fires > 10 ac, decreased snowpack Snowmelt rates increased Evaporation and sublimation greater

Table 12. Comparison of observed and estimated peak flows using USGS regression method from 10 year-24 hour storm event one year after the 2000 Skalkaho/Valley Complex Fires in the Bitterroot National Forest, Montana (unpublished data, Story, 2002)

Watershed (Creek)	Acres	% high burn	2001 observed Q_{10} (cfs)	Estimated Q_{10} (cfs)		
				Unburned[1]	2000 burned[2]	2001 burned[3]
Medicine Tree	4918	30	307	102	173	122[4]
Doran	4064	70	574	86	226	126
Lyman	3975	15	485	84	113	92
Laird	6222	60	613	125	300	175
Reimel (entire)	6154	30	210	150	255	180
Maynard	3395	60	377	89	214	125
Reimel	5050	30	187	126	214	151
Camp	5299	10	103	132	163	141
Cameron	21844	20	282	381	559	432
Warm Spring	6712	20	312	134	197	152

[1] from Omang (1992)

[2] Assumed that high soil burn severity areas are 1/3 water repellency with a 10 times increase in surface runoff

[3] Assumed that high soil burn severity areas are 1/6 water repellency with a 10 times increase in surface runoff

[4] Estimated Medicine Tree Creek Q_{10} in 2001

= (% high burn)×(unburned Q_{10})×(1/6 water repellency)×(10 times runoff increase) + (100% – % high burn)×(unburned Q_{10})

= (30%)×(102 cfs)×(1/6)×(10) + (100% – 70%)×(102 cfs)

= 122 cfs

Table 13. Description of NRCS Hydrologic Soil Group (USDA SCS, 1991)

Group	Description	Minimum infiltration rate (inch/h)
A	Low runoff potential and high infiltration rates, and consists chiefly of sands and gravels.	Greater than 0.30
B	Moderate infiltration rates, and have moderately fine to moderately coarse texture.	0.15–0.30
C	Low infiltration rates, and consists chiefly of soils having a layer that impedes downward movement of water and soils of moderately fine to fine texture.	0.05–0.15
D	High runoff potential and very low infiltration rates, and consists mainly of clay soils, soils with a permanent high water table, or shallow soils over nearly impervious material.	Less than 0.05

Table 14. Post-fire curve numbers (CNs) for various burn severities (Livingston and others, 2005)

Soil burn severity	Estimated CN
Unburned	55-75
Low	80-83
Moderate, without water repellent soils	87
Moderate, with water repellent soils	89
High, without water repellent soils	92
High, with water repellent soils	95

Table 15. Variations in Wildfire Hydrologic Impact (WHI) classification due to high soil burn severity (Livingston and others, 2005)

Percentage of subbasins with a high soil burn severity	Wildfire Hydrologic Impact classification
0-6	Low
7-48	Moderate
49-80	Severe

Table 16. Post-fire curve numbers (CNs) for various burn severities based on the Bitterroot National Forest, Montana (Cerrelli, 2005)

Soil burn severity	Sub-category	Estimated CN
High[1]	HSG[2] A	64
	HSG B	78
	HSG C	85
	HSG D	88
Moderate		Use cover type[3] in Fair condition
Low and Unburned	North and East facing slopes	Use cover type in Good condition
	South and West facing slopes	Use cover type between Fair and Good conditions
Any	Water repellent soils	[4]94

[1] High burn severity areas were assumed to have attained at least 30% ground cover consisting of vegetation, duff, thick ash, or woody debris by June of the following year after the fire, and the CN values were from three Montana NRCS engineers with hydrologic evaluation experience.
[2] Hydrologic Soil Group in table 13.
[3] From table D.2 and D.3.
[4] Rule of thumb by Montana NRCS.

Table 17. b and I_{30}^{thresh} values in the rainfall-discharge relation from the Rendija Canyon watershed after the 2000 Cerro Grande Fire, New Mexico (Moody and others, 2007)

Year	b	I_{30}^{thresh} (mm h^{-1})	r^2	p
2001	0.50	7.6	0.73	< 0.001
2002	0.43	11.1	0.52	0.001
2001 and 2002[1]	0.47	8.5	0.63	< 0.001

[1] The values of b and I_{30}^{thresh} in 2001 and 2002 are not significantly different. Therefore, they were combined.

Table 18. Comparison of observed and estimated peak flow using Kuyumjian's rule of thumb from various rainfall intensities (> 0.5 inch h^{-1}) for 2001 in four high severity burn subwatersheds of Rendija Canyon after the 2000 Cerro Grande Fire, New Mexico (Moody and others, 2007)

Watershed	Date	Rainfall intensity I_{30} (inch h^{-1})	Peak flow per unit drainage area (cfs $mile^{-2}$)	
			Observed	Estimated by rule of thumb[1]
3	2 Jul	2.07	686	622
3	13 Jul	0.88	151	263
3	9 Aug	1.50	405	449
9	2 Jul	0.90	41	269
9	26 Jul	1.45	777	435
9	9 Aug	0.59	28	177
9	11 Aug	0.90	154	270
11	2 Jul	1.69	461	508
11	26 Jul	1.30	333	389
11	11 Aug	1.28	333	384
13	2 Jul	0.65	65	195
13	2 Jul	1.13	182	339
13	2 Jul	1.10	43	331
13	11 Jul	0.73	39	219
13	11 Aug	1.28	264	384

[1] Bulking factor is not considered only to compare observed peak flow.

Table 19. WinTR-55 variables and their ranges (USDA NRCSb, 2005)

Variable	Range
Minimum area	No absolute minimum area. The user should carefu examine results from sub-area less than 1 acre.
Maximum area	25 square miles (6,500 hectares)
Number of sub-watersheds	1–10
Time of concentration for any sub-area	0.1 hour $\leq T_c \leq$ 10 hour
Number of reaches	0–10
Type of reaches	Channel or structure
Reach routing	Muskingum–Cunge
Structure routing	Storage–indication
Structure types	Pipe or weir
Structural trial sizes	1–3
Rainfall depth	Default or user-defined 0–50 inches (0–1,270 mm)
Rainfall distributions	NRCS Type I, IA, II, III (figure 4), NM60, NM65, NM70, NM75, or user-defined
Rainfall duration	24-hour
Dimensionless unit hydrograph	Standard peak rate factor 484, or user-defined

Table 20. Hydrological analysis 2 year, post-fire equivalent flood level using TR-55 for the 2002 Bullock Fire in the Coronado National Forest, Arizona (Lefevre and others, 2002)

Site name	2 year post-fire equiv		Q_2 (cfs)	Q_5 (cfs)	Q_{10} (cfs)	Q_{25} (cfs)	Q_{50} (cfs)	Q_{100} (cfs)
Bear Canyon: main canyon at highway	25	Pre	89	220	326	**535**	668	847
		Post	**445**	734	944	1,336	1,566	1,849
Bear Canyon: west canyon at highway	25	Pre	9	21	31	**50**	62	81
		Post	**38**	62	79	111	130	158
Willow Canyon summer home area at crossing	25	Pre	1	5	10	**27**	41	63
		Post	**18**	49	74	123	155	197
Rose Canyon campground at lower crossing	5	Pre	2	**9**	16	44	68	111
		Post	**10**	34	62	123	163	227
Barnum Rock at highway	100+	Pre	0	1	2	6	9	**13**
		Post	**17**	28	36	50	58	69
Sollers at highway	100	Pre	0	1	2	6	9	**15**
		Post	**12**	22	29	44	52	66
Sollers West at highway	100	Pre	0	2	3	8	12	**19**
		Post	**22**	36	45	63	74	90
Slide Area at highway	50	Pre	0	1	2	5	**8**	12
		Post	**9**	16	21	31	37	46
Slide Area West at highway	50	Pre	0	1	1	4	**6**	9
		Post	**5**	9	12	18	21	27
Incinerator Ridge East at highway	100	Pre	0	1	1	3	4	**6**
		Post	**7**	10	13	18	21	25
Incinerator Ridge at highway	50	Pre	0	1	1	4	**6**	9
		Post	**5**	10	13	20	24	31
Bear Willow summer home area	100+	Pre	0	0	1	2	3	**4**
		Post	**7**	11	13	17	20	23
Control Road at Green Springs	100	Pre	1	2	5	12	17	**26**
		Post	**30**	48	61	84	98	118
Marble Peak at Mine entrance	50	Pre	11	31	52	81	**102**	136
		Post	**103**	158	204	262	301	360
Lone Wolf Ranch at Eastern property line	10	Pre	15	35	**55**	83	103	135
		Post	**55**	93	128	173	202	246

Table 21. Runoff and erosion estimation using the WEPP model for the 2006 Red Eagle Fire, Montana (Sirucek and others, 2006)

	Runoff (inch)	Soil erosion (tons ac^{-1})	Number of rainfall events	Number of snowmelt events
Pre-fire conditions	0.18	0.04	2	0
Post-fire conditions	3.08	127	79	14

Table 22. Pre- and post-fire WATBAL comparison for the 2000 Crooked Fire in the Clearwater National Forest, Idaho, based on fire perimeter as of August 28, 2000. All values are percent increase over baseline condition (Jones, 2000)

Watershed	- - - - - - - - Pre-fire - - - - - - - -				- - - - - - - - Post-fire - - - - - - - -			
	Sed[1] (%)	Q_{aa}[2] (%)	Q_{pk}[3] (%)	T_{pk}[4] (%)	Sed (%)	Q_{aa} (%)	Q_{pk} (%)	T_{pk} (%)
Haskell	[5]48	8	8	9	104	15	16	17
Rock	31	5	5	5	295	18	20	19
Pack	9	9	9	10	9	9	9	10
Lower Crooked	14	5	5	6	109	15	16	17
Crooked @ mouth	7	2	2	3	22	3	3	4

[1] Sediment.
[2] Annual average flow.
[3] Peak flow.
[4] Time to peak.
[5] Haskell watershed in pre-fire condition produces 48% more sediment than baseline condition.

Table 23. Flow capacity for circular and pipe-arch culverts (Landowners Reference Manual, 1994; Robison and others, 1999)

Circular Culverts			*Pipe-Arch Culverts*		
Diameter (inches)	Cross-section area culvert (ft^2)	Maximum flow in culvert (cfs)	Span × Rise (ft and/or inches)	Cross-section area culvert (ft^2)	Maximum flow in culvert (cfs)
15	1.2	3.5	22″ × 13″	1.6	4.5
18	1.8	5	25″ × 16″	2.2	7
21	2.4	8	29″ × 18″	2.9	10
24	3.1	11	36″ × 22″	4.3	16
27	4	15	43″ × 27″	6.4	26
30	4.9	20	50″ × 31″	8.5	37
33	5.9	25	58″ × 36″	11.4	55
36	7.1	31	65″ × 40″	14.2	70
42	9.6	46	72″ × 44″	17.3	90
48	12.6	64	6′-1″ × 4′-7″	22	130
54	15.9	87	7′-0″ × 5′-1″	28	170
60	19.6	113	8′-2″ × 5′-9″	38	240
66	23.8	145	9′-6″ × 6′-5″	48	340
72	28.3	178	11′-5″ × 7′-3″	63	470
78	33.2	219	12′-10″ × 8′-4″	85	650
84	38.5	262	15′-4″ × 9′-3″	107	930
90	44.2	313			
96	50.3	367			
102	56.7	427			
108	63.6	491			
114	70.9	556			
120	78.5	645			
132	95	840			
144	113.1	1,000			

Typical case of ditch relief culvert on forestlands was assumed, which is that the culvert is inlet-controlled, and projecting inlet and headwater depth is equal to diameter or height of culvert.

Table 24. Permissible velocity to withstand erosion (Watkins and Fiddes, 1984; Novak and others, 2001)

Surface type	50 percentile size (mm)	Permissible velocity ($m\ s^{-1}$)
Fine silt	—	0.25–0.8
Sandy clay of low density	—	0.4
Coarse silt, fine sand	0.05	
Fine sand (non-colloidal)	0.25	0.6
Sandy loam (non-colloidal)	—	0.7
Sandy clay of medium density	—	
Silt loam	—	0.8
Medium sand	1.0	
Dense clay	—	
Volcanic ash	—	1.0
Coarse sand	2.5	
Stiff clay	—	
Graded loam to cobbles	—	1.5
Alluvial silt (colloidal)	—	
Graded silt to cobbles (colloidal)	—	1.6
Gravel (medium to fine)	5.0	1.1
Gravel (coarse to medium)	10	1.4
Coarse gravel and cobbles	25	1.9
Cobbles	40	2.4
Cobbles	100	3.6
Bitumen-bound macadam[1]	—	6.0
Asphalt	—	7.0

[1] Type of road construction. It consists of three layers of stones that interlock each others.

Table 25. Permissible velocities in vegetated channels (Watkins and Fiddes, 1984)

Vegetation	% slope of drain	Permissible velocities (m s^{-1})	
		In stable soils	In erodible soils
Bermuda grass	0–5	2.4	1.8
(*Cynodon dactylon*)	5–10	2.1	1.5
Buffalo grass	0–5	2.1	1.5
(*Buchloe dactyloides*)	5–10	1.8	1.2

Table 26. Range of values of C for free flow or modular flow over the embankment (Novak and others, 2001)

Surface type	Range of *h/L*	Range of *C*
Paved surface	0.15	1.68
	0.20	1.69
	> 0.25	1.70
Gravel surface	0.15	1.63
	0.20	1.66
	0.25	1.69
	0.30	1.70

Table 27. Correction factor, *f* for submerged flow or non-modular flow (Novak and others, 2001)

Surface type	Range of $h_{d/s}/H$	f
Paved surface	≤ 0.80	1.00
	0.90	0.93
	0.95	0.80
	0.99	0.50
Gravel surface	≤ 0.75	1.00
	0.80	0.98
	0.90	0.88
	0.95	0.68
	0.98	0.50

Table 28. List of gray literature obtained from BAER interviews

Literature	USGS regression	NRCS CN	TR-55	WEPP	R1/R4 sediment	Culvert sizing	Rolling dip/water bar	Culvert survey	Evaluation of treatments[1]
Cahoon (2005)						×			
Coronado National Forest (2003)		×							
Dixon (2008)	×								
Frazier and others (2005)									×
Furniss (2002)							×		
Gerhardt (2005)	×								
Gerhardt (2006a)		×							
Gerhardt (2006b)		×							
Higginson and Jarnecke (2007)		×							
Johnson (2003)									×
Johnson and Gould (2003)	×								
Jones and others (2006)	×								
Kuyumajian		×							
Lefevre and others (2002)			×						
Parret and others (2004)	×								
Sirucek and others (2006)	×			×				×	
Solt and Muir (2006)		×							
Story (2003)	×	×							
Story and others (2006)	×			×	×				
Stuart (2000)		×						×	

[1] Evaluation of road treatment implementation.

Table 29. Data from significant precipitation storm events during 2001 at U.S. Geological Survey precipitation stations in Canyon Ferry area, Montana (Parrett and others, 2004)

Crittenden Gulch (site 27)					
7/17			7/30		
Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)	Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)
5	0.17	5	5	0.02	< 2
10	0.27	5	10	0.04	< 2
15	0.36	5–10	15	0.06	< 2
30	0.41	2–5	30	0.12	< 2
60	0.43	2–5	60	0.15	< 2
Daily total	0.70	< 2	Daily total	0.28	< 2

Upper Magpie Creek (site 29)			Lower Magpie Creek (site 30)		
7/17			7/17		
Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)	Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)
5	0.13	2	5	0.07	< 2
10	0.18	< 2	10	0.10	< 2
15	0.21	< 2	15	0.12	< 2
30	0.30	< 2	30	0.19	< 2
60	0.35	< 2	60	0.23	< 2
Daily total	0.58	< 2	Daily total	0.39	< 2

Table 30. Peak streamflow discharges and estimated recurrence interval during 2001 at U.S. Geological Survey streamflow-gaging stations in Canyon Ferry area, Montana (Parrett and others, 2004)

Station or stream name	Drainage area (mi^2)	Precip. station site number	Date of peak discharge	Peak discharge (cfs)	Estimated recurrence interval (year)[1]
Crittenden Gulch at mouth, near	2.3	27	7/17	[2]1,020	200
Helena	2.3	27	7/31	[2,3]60	5–10
Magpie Creek above Bar Gulch, near Helena	17.4	[4]29/30	7/17	405	50–100
Hellgate Gulch at Forest Service boundary, near Helena	9.2	30	7/17	[3]310	100–200

[1] Based on equations developed for ungaged sites in unburned areas by Parrett and Johnson (2004).
[2] Multiple peak flows from thunderstorms.
[3] Estimated discharge.
[4] Site 29 is located in upper basin, and site 30 nearby the streamflow-gaging station.

Table 31. Data from significant precipitation storm events during 2001 at U.S. Geological Survey precipitation stations in Ashland area, Montana (Parrett and others, 2004)

Upper Paget Creek (site 33) 6/30			Coal Bank Creek (site 34) 6/30		
Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)	Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)
5	0.56	100–500	5	0.14	< 2
10	0.75	25–50	10	0.28	< 2
15	086	25	15	0.29	< 2
30	0.95	10	30	0.29	< 2
60	0.96	5	60	0.29	< 2
Daily total	0.96	< 2	Daily total	0.29	< 2

Table 32. Peak streamflow discharges and estimated recurrence interval during 2001 at U.S. Geological Survey streamflow-gaging stations in Ashland area, Montana (Parrett and others, 2004)

Station or stream name	Drainage area (mi^2)	Precip. station site number	Date of peak discharge	Peak discharge (cfs)	Estimated recurrence interval (year)[1]
Home Creek near Ashland	35.4	33	6/30	[2]1,000	50–100
Newell Creek near Ashland	4.3	33	6/30	400	50–100
Chromo Creek near Ashland	5.2	33	6/30	1,220	> 500
Brain Creek near Ashland	8.0	33	6/30	3,200	> 500
Paget Creek near Fort Howes Ranger Station, near Otter	14.0	33	6/30	3,500	> 500
Hole-in-the-Wall Creek near Ashland	1.5	34	6/30	310	50–100
Dry Creek near Ashland	4.5	33	6/30	2,460	> 500
King Creek near Ashland	12.4	33	6/30	1,920	> 500

[1] Based on equations developed for ungaged sites in unburned areas by Parrett and Johnson (2004).

[2] Estimated discharge.

Table 33. Data from significant precipitation storm events during 2001 at U.S. Geological Survey precipitation stations in Bitterroot area, Montana (Parrett and others, 2004)

Laird Creek at mouth (site 3)					
7/20			7/21		
Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)	Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)
5	0.12	2	5	0.16	5
10	0.24	5	10	0.31	10
15	0.31	5	15	0.47	10–25
30	0.42	2–5	30	0.54	10
60	0.43	2–5	60	0.58	5–10
Daily total	0.44	< 2	Daily total	0.58	< 2
Laird Creek above Gilbert Creek (site 5)					
7/20			7/21		
Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)	Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)
5	0.21	10–25	5	0.15	5
10	0.35	10–25	10	0.22	2–5
15	0.38	10	15	0.30	5
30	0.42	2–5	30	0.35	2–5
60	0.43	< 2	60	0.47	2–5
Daily total	0.43	< 2	Daily total	0.61	< 2
North Rye Creek (site 7)			Burke Gulch (site 12)		
7/15			7/30		
Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)	Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)
5	0.22	10	5	0.04	< 2
10	0.35	10–25	10	0.06	< 2
15	0.44	10–25	15	0.07	< 2
30	0.54	10	30	0.09	< 2
60	0.62	5–10	60	0.12	< 2
Daily total	0.64	< 2	Daily total	0.78	< 2

Table 33. Data from significant precipitation storm events during 2001 at U.S. Geological Survey precipitation stations in Bitterroot area, Montana (Parrett and others, 2004)—Continued

Sleeping Child Creek (site 14) 7/15		
Storm duration (minute)	Maximum rain depth (inch)	Recurrence interval (year)
5	0.21	5
10	0.38	10–25
15	0.53	25
30	0.66	10–25
60	0.76	10
Daily total	0.83	< 2

Table 34. Peak streamflow discharges and estimated recurrence interval during 2001 at U.S. Geological Survey streamflow-gaging stations in Bitterroot area, Montana (Parrett and others, 2004)

Station or stream name	Drainage area (mi^2)	Precip. station site number	Date of peak discharge	Peak discharge (cfs)	Estimated recurrence interval (year)[1]
Little Sleeping Child Creek above Spring Gulch, near Hamilton	9.3	12	7/30	[1]35	2
Laird Creek near Sula	9.3	3	7/20 7/21	[2]210 [2]220	200–500 200–500
Laird Creek above Gilbert Creek, near Sula	5.1	5	7/20 7/21	[2]160 [2]160	200–500 200–500
North Rye Creek near Conner	17.5	7	7/15	260	100
Burke Gulch near Darby	6.5	12	7/30	3.3	< 2
Sleeping Child Creek near Hamilton	37.0	14	7/15	150	< 2
Unnamed tributary to Sleeping Child Creek at Hot Springs, near Hamilton	3.6	14	7/15	10	2
Unnamed tributary No. 7 to Sleeping Child Creek near Hamilton	1.8	14	7/15	[3]200	> 500

[1] Based on equations developed for ungaged sites in unburned areas by Parrett and Johnson (2004).
[2] Multiple peak flows from thunderstorms.
[3] Estimated discharge.

Table 35. Peak debris-flow discharges on July 15, 2001 at selected tributary sites in the Sleeping Child Creek drainage in Bitterroot area, Montana (Parrett and others, 2004)

Unnamed tributary to Sleeping Child Creek	Drainage area (mi^2)	Average channel slope ($ft\ ft^{-1}$)	Estimated peak flow (cfs)
No. 2	0.07	0.43	1,740
No. 3	0.09	0.47	1,860
No. 4	0.10	0.46	1,930
No. 5	0.28	0.31	7,860
No. 6	0.08	0.43	3,500
No. 8	0.41	0.16	2,730

Table 36. The burned acreages by fire severity associated with the 2003 Blackfoot Complex, Montana as of September 20, 2003 (Johnson and Gould, 2003)

Site name	Burn severity area			Total watershed size (ac)
	High (ac)	Moderate (ac)	Low and unburned (ac)	
Sullivan	28,936	1,721	274	30,931
Sullivan below Conner[1]	10,131	1,695	274	12,100
Goldie at HH Reservoir[2]	1,519	835	56	2,410
Goldie Creek at FR 9838[2]	935	479	0	1,114
Clayton	3,840	447	0	4,287

[1] This basin is not enclosed, but analyzed as a unit since this is only part of the Sullivan Creek watershed that was burned.
[2] Goldie at Hungry Horse reservoir.
[3] Goldie Creek at Forest Road 9383.

Table 37. Predicted pre- and post-fire, 100 year flows based on Omang (1992) for the 2003 Blackfoot Complex, Montana (Johnson and Gould, 2003)

Site name	Watershed area (ac)	Pre-fire predicted flow (cfs)	Flow increase factor[1]	Pre-fire predicted flow (cfs)
Sullivan	30,931	1,758	1.06	1,871
Sullivan below Conner[2]	12,100	716	1.16	832
Goldie at HH Reservoir[3]	2,410	187	1.37	256
Goldie Creek at FR 9838[4]	1,114	104	1.43	149
Clayton	4,287	340	1.10	375

[1] Assuming 1 % increase in flow for every 1 % of the contributing watershed area with high and moderate burn severity.
[2] This basin is not enclosed, but analyzed as a unit since this is only part of the Sullivan Creek watershed that was burned.
[3] Goldie at Hungry Horse reservoir.
[4] Goldie Creek at Forest Road 9383.

Table 38. Predicted pre- and post-fire flows based on Parrett and Johnson (2004) for the 2006 Red Eagle Fire, Montana (Sirucek and others, 2006)

Watershed name	Return interval (year)	Pre-fire predicted flow (cfs)	Flow increase factor[1]	Post-fire predicted flow (cfs)[2]
Divide Creek	2	284	1.486	422
	5	495		736
	10	615		914
	25	919		1,366
	50	1,308	—	Same
	100	1,885	—	Same
Red Eagle Creek	2	832	1.253	1,042
	5	1,292		1,619
	10	1,502		1,882
	25	2,088		2,616
	50	2,870	—	Same
	100	4,022	—	Same

[1] Assuming 1 % increase in flow for every 1 % of the contributing watershed area with high and moderate burn severity.

[2] Post-fire flow = Pre-fire flow × Flow increase factor.

Table 39. USGS regression method to calculate post-fire peak flow for large watersheds (> 5,000 ac) burned by the 2006 Derby Fire, Montana (Story and others, 2006)

Watershed	Total acres	High + moderate burn severity		Modifier	Pre Q10 (cfs)	Pre Q25 (cfs)	Post Q10 (cfs)	Post Q25 (cfs)
		(ac)	(%)					
Bad Canyon	12,239	2,685	21.9	1.219	411	677	501	826
Trout Creek	16,866	5,801	34.4	1.344	516	877	693	1179

Table 40. Culvert analysis for 100 year flood flow for Payette National Forest, Idaho using USGS regression method (Dixon, 2008)

Road number	Drainage area (mi^2)	Forest cover[1] (%)	Thomas and others[2]			Q & H[3]
			Q_{10} (cfs)	Q_{50} (cfs)	Q_{100} (cfs)	Q_{100} (cfs)
50004	0.46	20	24.4	36.7	43.7	42.2
50004	0.56	65	22.5	33.8	40.2	49.1
51823	0.45	65	18.6	27.9	33.2	41.5
51822	0.29	65	12.7	19.0	22.6	29.5

[1] Estimated from aerial photo.
[2] Thomas and others (1997).
[3] Quillian and Harenberg (1982).

Table 41. Local precipitation-frequency values from NOAA Atlas 2 for the 2005 Blackerby Fire, Idaho (Miller and others, 1973; Gerhardt, 2006)

Return Interval	Rainfall Duration (inches)		
	30 minute	6 hour	24 hour
2-year	0.32	0.9	1.6
5-year	0.47	1.1	2.0
10-year	0.63	1.3	2.4
25-year	0.79	1.5	2.9

Table 42. NRCS peak flow discharge model output in 2nd post-fire period, one year after the 2005 Blackerby Fire, Idaho (Gerhardt, 2006)

Return Interval	Peak flow rate	
	cfs[1]	cfsm[2]
2-year	23	18
5-year	50	40
10-year	85	67
25-year	138	109

[1] cubic feet per second
[2] cfs per square mile

Table 43. Observed flood and debris flow on May 19, 2006, one year after the 2005 Blackerby Fire, Idaho (Gerhardt, 2006)

Observed Discharge	Peak flow rate	
	cfs[1]	cfsm[2]
Flood flow	71	56
Debris flow	620	492

[1] cubic feet per second
[2] cfs per square mile

Table 44. Estimated post-fire time of concentration (T_c) and peak flows for 10 year, 24 hour storm (Q_{10}) using FIRE HYDRO (Cerrelli, 2005) for the 2000 Maudlow Fire, Montana (Stuart, 2000)

Watershed	T_c (hour)	Q_{10} (cfs)
Sulphur Bar	1.8	172
Tributary to Sulphur Bar	0.8	70
Dry Creek	2.6	532
Timber Gulch	1.0	66

Table 45. Pre- and post-fire modeling results for the selected watersheds for 10-year, 30 minute storm (0.77 inch) on the 2007 Salt Creek Fire, Utah, using the WILDCAT4 (Hawkins and Greenberg, 1990) (Higginson and Jarnecke, 2007)

Watershed	Area (mi^2)	Pre-fire modeling			Post-fire modeling		
		Total runoff (ac-ft)	T_c[1] (hr)	Peak flow (cfs)	Total runoff (ac-ft)	T_c (hr)	Peak flow (cfs)
Rolley Canyon	1.2	6.0	0.76	107	29.9	0.67	522
Serviceberry Hollow	4.0	10.4	1.01	147	32.9	0.90	458
Water Hollow Tributary #1	0.7	2.9	0.59	82	9.6	0.45	270
Water Hollow Tributary #2	1.8	6.9	0.73	153	20.7	0.67	440
Rocky Ridge Creek	1.2	1.3	0.64	35	5.1	0.54	132

[1] Time of concentration

Table 46. Pre- and post-fire modeling results for the selected watersheds for 25-year, 30 minute storm (1.0 inch) on the 2007 Salt Creek Fire, Utah, using the WILDCAT4 (Hawkins and Greenberg, 1990) (Higginson and Jarnecke, 2007)

Watershed	Area (mi^2)	Pre-fire modeling			Post-fire modeling		
		Total runoff (ac-ft)	T_c[1] (hr)	Peak flow (cfs)	Total runoff (ac-ft)	T_c (hr)	Peak flow (cfs)
Rolley Canyon	1.2	11.2	0.76	201	39.7	0.67	716
Serviceberry Hollow	4.0	20.8	1.01	290	49.2	0.90	687
Water Hollow Tributary #1	0.7	5.0	0.54	143	12.6	0.45	354
Water Hollow Tributary #2	1.8	14.3	0.73	312	31.8	0.67	680
Rocky Ridge Creek	1.2	3.0	0.64	81	8.1	0.54	209

[1] Time of concentration

Table 47. Pre- and post-fire Curve Number for the 2003 Aspen Fire, Arizona (U.S. Forest Service Coronado National Forest. 2003)

Hydrologic soil group	Pre-fire CN	Post-fire CN		
		High burn severity	Moderate burn severity	Low burn severity
B	56	65	—	—
C	67	70–75	80	90
D	77	80–85	90	95

Table 48. Recommended maximum spacing for waterbars on temporary roads, trails, skid trails, and firelines (Furniss, 2002)

Gradient (%)	Erosion hazard rating for area			
	4–5 Low (ft)	6–8 Medium (ft)	9–10 High (ft)	11–13 Very high (ft)
1–6	400	350	300	250
7–9	300	250	200	150
10–14	200	175	150	125
15–20	150	120	90	60

Table 49. Summary information for culverts affected by the 2006 Red Eagle Fire, Montana (Sirucek and others, 2006)

Stream	Road name	Culvert size (inch)	Height of culvert rust-line (inch)	Stream bank-full width (inch)	% of basin burned above culvert[1]	Recommendation
Fox Creek	Truck trail road	18″	9″ depth	18–24″	H	Clean out
Livermore	A road	18″	10–11″	36–38″	H	Replace w/ 24″ squash[2] CMP[3]
Livermore	A road	Native wood (collapsed)	NA	24–28″	H	Replace w/ 36″ squash CMP
Livermore	A road	24″	13″	24–28″	H	Replace w/ 36″ squash CMP
Livermore	A road	30″	5″	40–48″	H	Clean out
Livermore	A road	36″	20″	44–48″	L	Clean out
Livermore	A road	24″	7″	44–48″	L	Clean out
South Fork Milk	Milk road spur	26″ by 40″ (squashed)	New, no rustline, 12″ flow depth at examination	55–65″	H	Clean out
South Fork Milk	Milk road spur	24″	14″	36–40″	H	Replace w/ 36″ squash CMP
Fox Creek	A road	36″	24″ newly constructed beaver exposure	10 ft	H	Replace w/ 48″ squash CMP
Fox Creek	A road	18″	6″	24″	H	Clean out
Fox Creek	A road	18″	Nearly filled w/ sediment	48″	H	Clean out
Fox Creek	D road	36″	18″ nearly blocked by old beaver fill, and compressed	6 ft	H	Replace w/ 48″ squash CMP
Fox Creek	B road	18″	2″	Draw	H	Upsize
Fox Creek	B road	18″	2″	Draw	H	Clean out
Fox Creek	B road	36″	10″	10 ft w/ beaver complex	H	Upsize culvert (72″ squash)
Fox Creek	B road	18″	Unknown	Draw	L	Clean out

[1] H = 75% or more of the basin burned with high and moderate burn severity; L = 50% or less.
[2] Pipe-arch culvert made by squashing 24″ culvert.
[3] Corrugated Metal Pipe.

Table 50. Culvert survey results to assess road and drainage hazard for the 2000 Maudlow Fire, Montana (Stuart, 2000)

Drainage	Culvert at risk	Locations	Diameter (inch)	Comments
Cedar Bar Creek	None			Rehab cat lines and hand lines.
Blacktail Creek	4190a	7N, 4E, S36b	18	Do not replace due to lack of burn area above culvert.
Sulphur Bar Creek	147a	7N, 4E, S34a	36	Remove.
	147b	6N, 4E, S1d	36	Clean debris from inlet.
	147c	6N, 4E, S12a	24	Clean debris from inlet.
	4187a	6N, 4E, S2a	36	Replace w/ 48″ countersunk pipe.
	4187b	6N, 4E, S2b	24	Consider temporary removal.
	4187c	6N, 4E, S35c	18	X-drain replace w/ fish passage.
Dry Creek	259a	6N, 4E, S24c	72 equiv	Pvt[1]; remove debris.
	259b	6N, 4E, S25a	72 equiv	Pvt; replace sagging culvert.
	259c	6N, 4E, S30b	18	Upgrade x-drain pipe.
	259d	6N, $e, S30a	18	Upgrade x-drain pipe.

[1] Pavement

Table 51. Evaluation of road treatment implementation for the 2003 Aspen Fire, Arizona (Johnson, 2003)

Road name	Treatment	Evaluation relative to goals	Evaluation method
Fern Ridge Road	Remove culverts	Culverts removed, road passable	Visual observation by forest engineer
Sykes Knob Road	Remove culverts	Culverts removed, road passable	Visual observation by forest engineer
Turkey Run Road	Remove culvert	Culvert removed, road passable	Visual observation by forest engineer
Marshall Gulch Road	Place trash rack at inlet to deflect material over road	Goal accomplished, trash rack placed	Trash rack observed in place
Summerhaven main road	Place trash racks at two culvert inlets to deflect material over road	Trash rack placed	Visual observation by hydrologists
Mt Lemmon Lookout	Remove culverts	Culverts removed, road passable	Visual observation by forest engineer
Road into Willow Creek	Armor and buttress three crossings	Culvert removed, road passable	Visual observation by forest engineer
Sabino Canyon Rec Road	Install concrete aprons on bridge approaches	Apron installed	Visual observation by forest engineer

Table 52. Summary of road treatments initially implemented and after the 2005 wet winter season for the 2003 Cedar Fire, California (Frazier and others, 2005)

Road number	Road name	Recommended treatments	
		Initially implemented	After the 2005 wet season
13S09	Dye Canyon	Further assessment needed	
13S10	Westside	Restore drainage function, construct/reconstruct dips and overside drains, riprap fill slopes, storm patrol, and BAER warning signs.	Restore drainage function, reconstruct dips, repair/replace damaged overside drains, re-install riprap (9.5 miles).
13S11	Cedar Creek	Restore drainage function, construct/reconstruct dips and overside drains, riprap fill slopes, storm patrol, and BAER warning signs.	Restore drainage function, reconstruct dips, repair/replace damaged overside drains, re-install riprap (3.8 miles).
14S03	Garnet Peak	No treatments recommended	
14S04	Deer Park	Restore drainage function and storm patrol.	Restore drainage function, reconstruct dips, repair/replace damaged overside drains, re-install riprap (3.3 miles).
14S05	Pine Creek	Restore drainage function and place riprap for fillslope protection.	Restore drainage function, repair/replace damaged overside drains, re-install riprap (7.0 miles).
14S07	Tule Springs	Restore drainage function, construct overside drains, riprap, storm patrol, and BAER warning signs.	Restore drainage function, reconstruct dips, repair/replace damaged overside drains, re-install riprap (4.0 miles).
14S08	Conejos Valley	Restore drainage function, storm patrol, and BAER warning signs.	
14S08	Dubois	Restore drainage function, rock dips, upsize culvert, storm patrol, BAER warning signs, and a metal end-section on an existing 60″ CMP[1].	
15S21	Miners	Replace and upsize an existing overside drain.	Restore drainage function, reconstruct dips, repair/replace overside drains, re-install riprap (1.2 miles w/ approx 50% on Capitan Grande Indian Reservation).
15S24	Goude	Restore drainage function and storm patrol.	
15S30	Anderson Truck Trail	Restore drainage function, construct dips and overside drains, place riprap at the end of existing overside drain flumes, storm patrol, and BAER warning signs.	Restore drainage function, reconstruct dips, repair/replace damaged overside drains, re-install riprap, replace two 30″×60″ CMP culverts, replace lost aggregate surfacing (1.6 miles plus 0.9 miles on private lands).

[1] Corrugated Metal Pipe.