Assessing the Hydrological and Erosional Effects of Wildland Fire

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Abstract

In the western United States wildland fires are increasing in frequency, size and severity resulting in the increased risk of severe hillslope erosion, flooding and sedimentation. Functionality has been incorporated into the Automated Geospatial Watershed Assessment Tool (AGWA) to assess the impacts of wildland fire on runoff and erosion. AGWA (see: www.tucson.ars.ag.gov/agwa or https://www.epa.gov/water-research/automated-geospatial-watershed-assessment-agwa-tool-hydrologic-modeling-and-watershed) is a GIS interface jointly developed by the USDA-Agricultural Research Service, the U.S. Environmental Protection Agency, the University of Arizona, and the University of Wyoming to automate the parameterization and execution of a suite of hydrologic and erosion models (RHEM, KINEROS2 and SWAT). Through an intuitive interface the user selects an outlet from which AGWA delineates and discretizes the watershed using a Digital Elevation Model (DEM). The watershed model elements are then intersected with terrain, soils, and land cover data layers to derive the requisite model input parameters. Based on a small sample of pre- and post-fire rainfall-runoff data, a method was developed to adjust model parameters as a function of the pre-fire vegetation cover and fire severity maps. To date AGWA was been used on over 52 wildland fires (> 3.8 million acres) by the Department of Interior Interagency Burned Area Emergency Response teams to assess the fire impacts on runoff and erosion and support the development of Burned Area Assessment Reports. Wildland fires typically occur in remote locations with limited metrological and hydrological data. Assessments also need to be completed quickly in order to develop plans to protect downstream communities, infrastructure and important resources. Typically, model calibration and validation are not feasible, hence relative change assessment (i.e. pre- versus post-fire) is done to identify at-risk areas. This paper will discuss the issues associated with relative change assessment and the implications to post-fire decision making.

Introduction

Hydrologic and erosion models can be applied for different uses such as exploratory, planning or regulatory/legal purposes (Harmel et al. 2014). Each of these purposes require different levels of confidence in the model output, with potentially high standards for regulatory/legal and low standards for exploratory. Importantly, how and where the models will be applied and how the model results will be utilized are important considerations when determining the acceptable level of uncertainty in model results.

This paper will discuss the application of the KINematic runoff and EROsion model (K2, Smith et al. 1995) within the Automated Geospatial Watershed Assessment tool (AGWA, Goodrich et al. 2012) to support Department of Interior Interagency Burned Area Emergency Response (BAER) teams to assess the fire impacts on runoff and erosion and support the development of Burned Area Assessment Reports. A Burned Area Assessment Report is a plan for post-fire stabilization and rehabilitation (Robichaud et al. 2014) in which treatments are recommended to mitigate adverse effects from the burned area on values-at-risk (VAR), such as life, property, and critical natural and cultural resources.

For this planning application models are used to assess the potential risk to an individual value. This requires being able to assess how the patterns of fire severity influence the hydrological and erosional response to specific locations within the burned area. A Burned Area Assessment Report also must be completed within two weeks of the fire's official containment. Wildland fires are usually located in areas with limited meteorological (precipitation, temperature) and hydrological (stream discharge) data making it difficult to calibrate and validate model predictions in order to gage the level of confidence in the model output. However, for this planning application the model's ability to identify areas in high vs low risk is more important while very high accuracy and precision in model predictions is less critical (Harmel et al. 2014).

AGWA Overview

AGWA (Goodrich et al. 2012) is a Geographic Information System (GIS) based watershed modeling tool. The guiding principles for the development of AGWA were that it: 1) provides simple, direct, transparent, and repeatable parameterization routines through an automated, intuitive interface; 2) is applicable to ungauged watersheds at multiple scales; 3) evaluates the impacts of management and is useful for scenario development; and, 4) uses free and commonly available GIS data layers.

The models currently incorporated in AGWA are KINEROS2 (K2 – KINematic runoff and EROsion model, Smith et al. 1995, Goodrich et al. 2012), RHEM (Rangeland Hydrology and Erosion Model, Hernandez et al. 2017), and SWAT (Soil and Water Assessment Tool version 2000 and version 2005, Arnold and Fohrer 2005). AGWA supports modeling along a continuum of spatial and temporal scales, ranging from hillslopes (~hectares) to large watersheds (>1000 km^2) and from individual storm events (minute time steps) to continuous simulation (daily time steps over multiple years). AGWA supports the parameterization and execution of hydrologic models for watershed modeling efforts by performing the following tasks: watershed delineation; watershed discretization into discrete model elements; watershed parameterization; precipitation definition; simulation creation; simulation execution; and simulation results visualization (
Figure 1). Various data are required to support this functionality, including: a raster-based DEM (digital elevation model); a polygon soil map (NRCS SSURGO, NRCS STATSGO, or FAO soil maps); and a classified, raster-based land cover (NLCD, NALC, and GAP/LANDFIRE datasets are supported via provided look-up tables; however, other datasets may also be used if accompanied with a related look-up table). AGWA does not require observed precipitation or

runoff to drive the models when used for relative assessment/differencing between scenarios. For precipitation input, AGWA can use user-defined depths and durations, user-defined hyetographs, or design storms to drive K2, and included weather station-based generated, daily precipitation (U.S. only) to drive SWAT. However, high-quality rainfall-runoff observations are required for calibration and confidence in quantitative model predictions (Goodrich et al. 2012).

K2 is the primary model used for post-fire assessments. K2 predicts the runoff volume, peak flow, and sediment yield from individual hillslope elements to medium size watersheds. K2 is an event-oriented, physically-based model describing the processes of interception, infiltration, surface runoff, and erosion. A watershed is represented as a series of overland flow model elements (curvilinear or planar) and channels in a cascade, on which the processes of infiltration, interception, retention, erosion, sediment detachment, transport and deposition are all explicitly treated. Partial differential equations are used to describe these processes and are solved by finite difference techniques. Runoff is routed using the kinematic wave equations for overland and channel flow. These equations, and those for erosion and sediment transport, are solved using a four-point implicit finite difference method (Smith et al. 1995). Two important model parameters related to representing the impact of wildland fire are the soil saturated hydraulic conductivity (Ks) used in the Smith-Parlange infiltration equation and the Manning's n roughness factor (n) for overland flow (Semmens et al. 2008).

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Barlow (2017) recently developed a tool for AGWA to quickly map inundated areas adjacent to stream channels with relatively simple geometry and downstream conditions (without major constriction and backwater). The tool uses algorithms from the U.S. Army Corps of Engineers Hydrologic Engineering Center HEC-2 model (CEIWR-HEC 1990). Using peak flow outputs from K2 in AGWA, the tool will allow resource managers to quickly determine if a VAR is at risk for flooding or severe erosion after a fire. AGWA also has the ability to assess common post-fire treatments, such as the application of straw mulch.

Post-Fire Assessment Tool

Wildland fire can affect both the volume and peak flow of runoff resulting from a rain event. The research clearly indicates that the biggest impact of fire is on peak flows, not on runoff volumes (Campbell et al. 1977, Canfield et al. 2005, Ice et al. 2004, Moody and Martin 2001, Neary et al. 2003, Shakesby and Doerr 2006, Springer and Hawkins 2005). Figure 2 shows the pre- and post-fire streamflow response for a small watershed in the Santa Catalina Mountains in southeastern Arizona, USA (Canfield et al. 2005). Although the post-fire (right) rainfall event was smaller (44 mm vs. 54 mm, but similar pattern) and had a small runoff volume (4.6 mm vs. 10 mm) it had significantly higher peak runoff (4.32 mm/hr vs. 0.16 mm/hr). Note that the post-fire event had duration in minutes (~ 4 hours) compared to the pre-fire event where the duration is in days (~ 11 days).

Parameterization

Parameterization procedures were developed to capture the effects of wildland fire on two important hydrologic parameters: Soil Saturated Hydraulic Conductivity (Ks) and the Overland Flow Manning's n roughness value (n), where Ks primarily influences the volume of runoff and n primarily influences the rate of runoff. The procedures for post-fire Ks adjustments are relatively conservative compared to the post-fire adjustments of Manning's n.

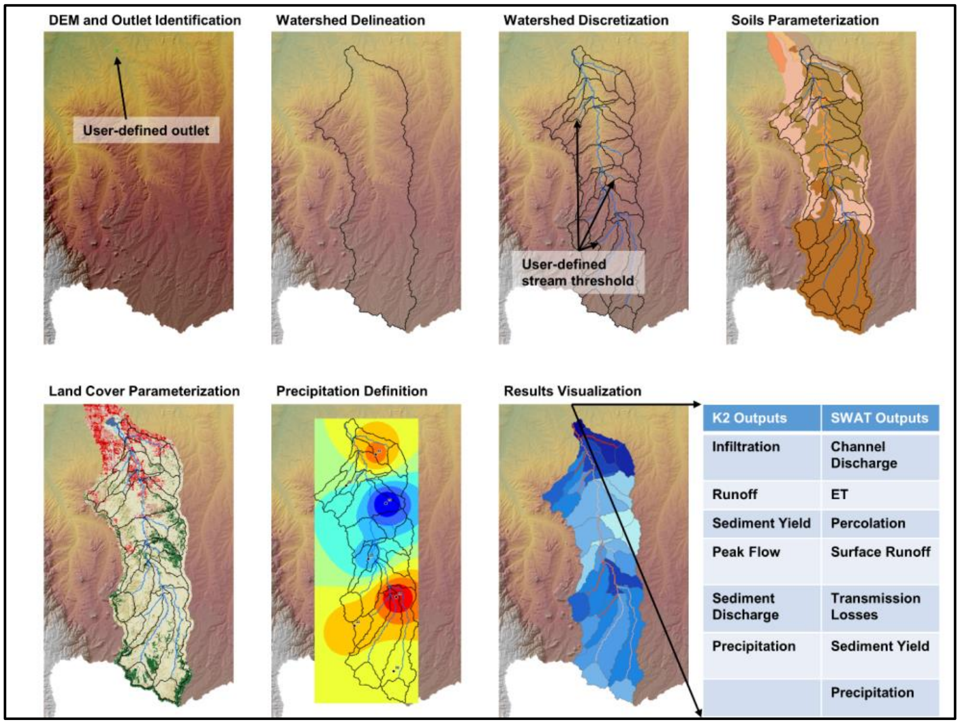

Figure 1. The required steps in AGWA to perform a watershed assessment. A DEM is used to delineate the watershed and subdivide it into model elements (i.e. hillslopes and channels for K2 and subwatersheds and channels for SWAT). The model elements are parameterized based on the DEM, soils, and land cover layers. The precipitation input is then selected from various sources. After the model is executed, the results are imported and visualized in the GIS.

The soils database provides a texture-based estimate (Rawls et al. 1982) of saturated hydraulic conductivity (Ks), and the land cover layer provides information associated with land cover types, such as percent cover, interception, and hydraulic roughness (Manning's n). Ks is then adjusted for percent cover using Equation 1 developed by Stone et al. (1992):

$$Ks = Ks_{Soil} * e^{0.0105*CC} \quad (1)$$

where Ks is the saturated hydraulic conductivity (mm/hr), Ks_{Soil} is the saturated hydraulic conductivity obtained from soil texture (mm/hr), and CC is the canopy cover in percent. Pre-fire CC values are set to nominal conditions for the NLCD cover class based on NLCD descriptions and CC values for the general classes found in the literature.

Using a Burned Area Reflectance Classification (BARC) that preferably has been field-verified to reflect the soil burn severity, the pre-fire land cover layer is reclassified to reflect the effect of burn severity. Based on the burn severity (High, Moderate, and Low), the percent canopy cover and Manning's n values are changed (see Table 1; Canfield et al. 2005). The final result of the reclassification is a mosaic of unburned areas and areas with different burn severity. The post-fire parameterization uses the reclassified land-cover with the changed CC and Manning's n

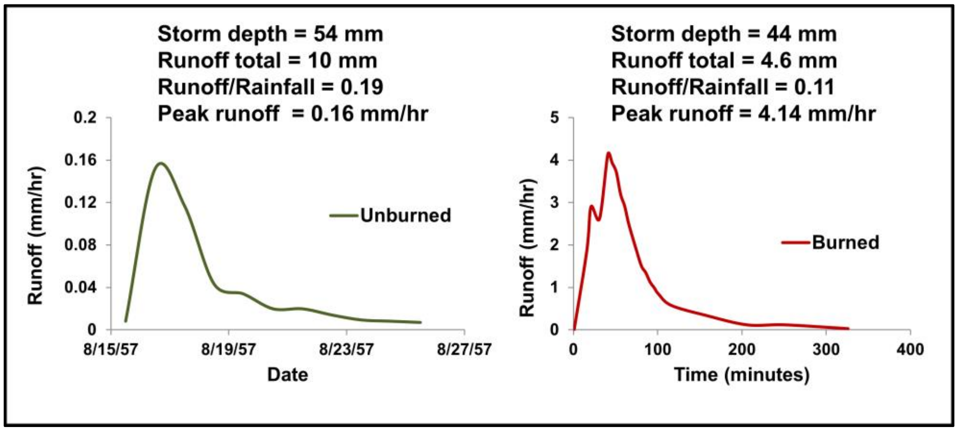

Figure 2. Pre-fire and Post-fire hydrographs recorded at Marshall Gulch, Arizona. This figure illustrates the difference in storm response for unburned and burned conditions (from Canfield et al. 2005, Scott 2016).

Table 1. Canopy cover and Manning's n for unburned and low, moderate, and high severity burns as assigned by AGWA (based on Canfield et al. 2005, Burns et al. 2013)

Change from Unburned Condition				
Percent Cover				
NLCD Land Cover Class	**Unburned**	**Low Severity**	**Moderate Severity**	**High Severity**
Deciduous Forest	50	43	34	25
Evergreen Forest	50	43	34	25
Mixed Forest	50	43	34	25
Scrub	25	21	17	12
Grasslands/Herbaceous	25	21	17	12
Manning's n				
	Unburned	**Low Severity**	**Moderate Severity**	**High Severity**
Deciduous Forest	0.4	0.199	0.06	0.017
Evergreen Forest	0.8	0.199	0.058	0.017
Mixed Forest	0.6	0.199	0.058	0.017
Scrub	0.055	0.01	0.005	0.003
Grasslands/Herbaceous	0.13	0.024	0.012	0.007

values, and also adjusts Ks using the new canopy cover value for the burnt area, assigning parameter values for each modeling element using an area-weighted average. The reduction in canopy cover for NLCD classes, as a function of burn severity, was obtained via personal communication with P. Robichaud (2004, U.S. Forest Service, Rocky Mountain Research Station, 1221 South Main Street, Moscow, Idaho, 83843). Percent canopy cover is not part of the NLCD national data layers that are updated roughly every five years. The LANDFIRE program, initiated in 2009 by the U.S. Department of the Interior and U.S. Forest Service (https://www.landfire.gov/) is providing a variety of land cover, land use, and change-over-time geospatial products nationally. LANDFIRE products include a greater number of land classes than NLCD, include canopy cover for those classes, and are updated on a two-year basis. The AGWA team is in the process of updating AGWA tools to utilize LANDFIRE geospatial products. This will provide better pre-fire vegetation and canopy cover conditions, which results in more localized parameter information for both pre-fire and post-fire parameterizations.

Validation

Chen et al. (2013) evaluated the Rule of Thumb method, Modified Rational Method (MODRAT), HEC-HMS Curve Number (CN) model, and KINEROS2 model for assessing the impacts of wildland fires. In their investigation, all models were applied to paired burned and unburned watersheds, as well as unburned and burned conditions in a watershed that had both pre-fire and post-fire observed rainfall and runoff events. These watersheds were located in the San Dimas National Forest in southern California. The unburned watershed was 5.54 km^2 and the burned watershed was 6.16 km^2. The burned watershed was 31.6 percent burned in the 1953 Barrett fire, including 18.2 percent severely burned and 13.4 percent partially burned areas. The burn occurred in the upper portion of the watershed. The vegetation in these watersheds was composed of chaparral, semi-barren areas, and woodland consisting of oak, maple, and big cone Douglas fir. Data was recorded at several rain gauges within the watersheds, including intensity recording gauges. Stream flow measurements were taken at the outlet of each watershed. The HEC-HMS CN approach and the KINEROS2 model both create complete hydrographs and were investigated more thoroughly by the authors. It was found that the pre-fire storms were better simulated by the HEC-HMS model and that the post-fire storms were better predicted by the KINEROS2 model. Chen et al. (2013) postulate that this had to do with how surface runoff is generated in each model. KINEROS2 treats surface runoff generation as infiltration excess whereas the Curve Number method employed in HEC-HMS is more consistent with saturation excess runoff generation.

Sheppard (2016) also found that the current parameterization scheme in AGWA provides reasonable post-fire estimates for relative change risk assessments. Sheppard (2016) calibrated K2/AGWA for five small burnt watersheds in Arizona, Colorado, and New Mexico. Sheppard (2016) found a high degree of variability in the calibration results for Ks and Manning's n across watersheds and determined that the AGWA parameterization process provided results that fit within the range of calibrated values. Sheppard (2016) found that adjusting Ks based on rainfall intensity significantly improved the modeling results and suggested that adding this adjustment procedure would improve the K2/AGWA results more than modifying the current parametrization procedures.

The Natural Resources Conservation Service (2016) evaluated AGWA for predicting bulking and peak discharge on the Dump Fire in Saratoga Springs, Utah, and found it worked reasonably well although it tended to underestimate sediment yield. Herbst et al. (2013) evaluated AGWA's ability to estimate sediment loads (megagrams per year) for the Sierra Nevada and Central Coast regions in California. With no calibration AGWA overestimated sediment load by 72 percent in the Sierra Nevada region and by 77 percent in the Central Coast region. The authors noted that with local adjustments the AGWA sediment predictions were improved.

Post-fire Risk Assessment

Conceptually, K2 represents a watershed as a series of hillslope elements and channel reaches. Each hillslope element has its own set of parameters. Runoff and erosion are simulated for each hillslope element and routed to the channel reach. The channel reaches are linked together and route the runoff and sediment to the watershed outlet. This distributed structure allows the modeling results to be mapped so areas at risk can be assessed (See Figure 3).

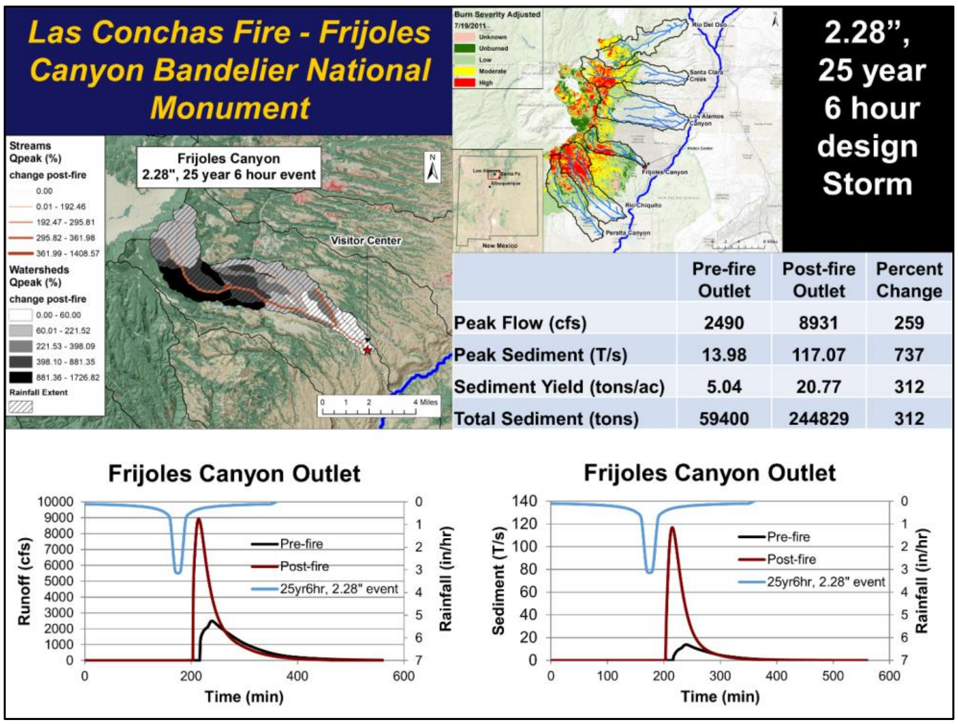

Figure 3. Typical post-fire assessment results produced by AGWA. For this example, the Value-At-Risk (VAR) was the Bandelier National Monument Visitor Center

As illustrated in Figure 3 AGWA has visualization tools that allow the user to determine quickly which hillslopes or channel reaches are likely at risk. After pre-fire and post-fire simulations are complete, the user can evaluate the relative change using either absolute values or percentages. A graduated color ramp is used so areas with high risk can be easily identified. AGWA allows the user to insert pour points (i.e. location of values-at-risk) within a larger watershed to provide results specifically for that location. The user can also get additional information on the risk by clicking on the area in question and obtain either tabular data or a hydrology or sediment graph.

Sidman et al. (2016) examined how rainfall representation, the most sensitive input parameters in hydrologic modeling, affected the estimates of peak flow and the identification of at-risk locations within a watershed. The study used K2/AGWA to compare several spatial and temporal rainfall representations. The representations include: 1) Constant intensity applied in a spatially uniform patterns over the entire watershed; 2) Soil Conservation Service Type II hyetographs with rain applied uniformly over the entire watershed; 3) SCS-Type II hyetographs uniformly applied over only the burned area; and 4) space-time variable National Weather Service DHR radar data. The total rainfall depth for representations 1-3 was the watershed average rainfall depth based on the DHR radar data. In this analysis, K2 was parameterized using AGWA procedures without calibration.

Two large return period events were modeled by Sidman et al. (2016): North Creek at Zion National Park, Utah on August 21, 2007 after the Kolob Fire, and Frijoles Canyon at Bandelier National Monument, New Mexico on August 21, 2011 after the Las Conchas Fire. Figure 4 illustrates the effect of precipitation representation on estimating peak flow. In both cases the DHR radar observations, the best representation of rainfall temporal and spatial distribution available, provided the best results. It is worth noting that K2 with AGWA default parameters also estimated the peak flow well in both cases. In North Creek, DHR radar-rainfall inputs under-predicted peak flow by 18 percent and at Frijoles Canyon it over-predicted peak flow by 17 percent. This reinforces the importance of rainfall representation in model performance. K2/AGWA was not calibrated for either watershed and still showed peak flows within 20 percent of the USGS peak flow estimates (Sharrow (2012) for the North Creek, Monroe (2012) for the Frijoles Canyon).

In post-fire assessments, when a rainfall-runoff event has not yet occurred, an assumed rainfall distribution must be used for modeling, leading to the question of how rainfall representation affects the identification of at-risk locations within a watershed. The relative impact of the fire on peak flow for individual stream reaches and sediment yield from hillslope elements was evaluated using rainfall representations 1-3 noted previously, plus the 2-year, 30-minute design storm for southern Utah. Within the burned area, the stream reaches and hillslope model elements were sorted from high to low, with the largest value (i.e. peak flow or sediment yield) given the rank of 1, the second largest given the rank of 2, and so on. The ranks for the different rainfall representations were then compared using the Spearman's rank correlation coefficient (McBean and Rovers 1998). In general, the Spearman's correlation coefficients were high, pointing to agreement in rankings across the different representations. At North Creek, the average coefficient for stream reaches was 0.72, and the average for hillslopes was 0.94. At Frijoles Canyon, the average coefficient for stream reaches was 0.82, and the average for hillslopes was 0.78. These high correlation coefficients suggest that K2/AGWA is not sensitive to changes in rainfall representation when predicting areas with high relative change pre- and post-fire. The fact that rainfall representation does not greatly affect prediction of high-risk areas is important during a rapid post-fire assessment when future storm characteristics are not known.

Conclusion

The AGWA tool with the K2 model has proven to be a valuable tool for performing post-fire assessments and has been formally adopted by the US DOI National BAER teams for initial determination of risk to downstream values. Testing has shown that K2 captures post-fire peak floods well using the parameterization procedures in AGWA if rainfall data are available to represent the temporal and spatial pattern of rainfall. Importantly, AGWA/K2 can support the planning mission of the BAER teams in data poor environments. The relative change results that

AGWA/K2 provides can be used to identify areas of high risk. The AGWA simulations can be used to determine risk to life and property, assess potential risk of structural failure (e.g. culverts, bridges, and dams), and identify areas with high erosion that could be evaluated for hillslope treatments such as mulch and reseeding treatments that mitigate downstream impacts.

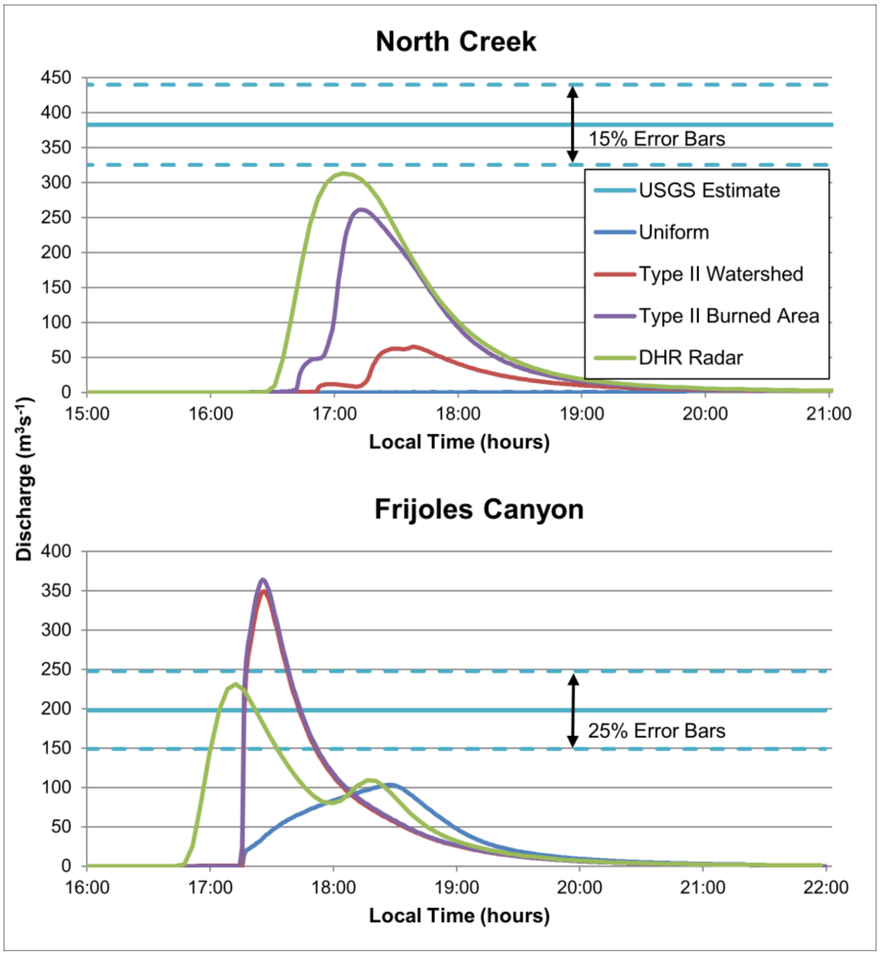

Figure 4. Hydrographs for modelled storms for North Creek, Zion National Park, and Frijoles Canyon, Bandelier National Monument. 'Uniform' represents uniform rainfall intensity over the entire watershed, "Type II Watershed" is a Soil Conservation Service (SCS 1972) Type II distribution over the entire watershed, "Type II Burned Area" is a SCS Type II distribution over just the burned area, 'DHR' is Digital Hybrid Reflectivity radar data from the National Weather Service for the actual storm event (August 1, 2007 at Zion and August 21, 2011 at Bandelier). The U.S. Geological Survey (USGS) peak flow and uncertainty estimates are based on post-flood indirect measurements and analysis (Monroe 2102, Sidman et al. 2016, Sharrow 2012).

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