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A coupled modeling approach to assess the impact of fuel treatments on post-wildfire runoff and erosion

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Abstract

The hydrological consequences of wildfires are among the most significant and long-lasting effects. Since wildfire severity impacts post-fire hydrological response, fuel treatments can be a useful tool for land managers to moderate this response. However, current models focus on only one aspect of the fire-watershed linkage (fuel treatments, fire behavior, fire severity, watershed responses). This study outlines a spatial modeling approach that couples three models used sequentially to allow managers to model the effects of fuel treatments on post-fire hydrological impacts. Case studies involving a planned prescribed fire at Zion National Park and a planned mechanical thinning at Bryce Canyon National Park were used to demonstrate the approach. Fuel treatments were modeled using FuelCalc and FlamMap within the Wildland Fire Assessment Tool (WFAT). The First Order Fire Effects Model (FOFEM) within WFAT was then used to evaluate the effectiveness of the fuel treatments by modeling wildfires on both treated and untreated landscapes. Post-wildfire hydrological response was then modeled using KINEROS2 within the Automated Geospatial Watershed Assessment Tool (AGWA). This coupled model approach could help managers estimate the impact of planned fuel treatments on wildfire severity and post-wildfire runoff/erosion, and compare various fuel treatment scenarios to optimize resources and maximize mitigation results.

50 word abstract:

Assessing the effectiveness of fuel treatments on reducing post-fire hydrologic response is an important challenge in fire management. We linked fuel treatment, wildfire, and hydrological models spatially to measure the impacts of fuel treatments on post-fire runoff and erosion in two case studies on National Park Service lands.

Introduction

The increase in large damaging wildfires in the western United States in recent decades has engaged the attention of scientists, Federal agencies, policy makers, and the public, who increasingly agree on the need to move away from total suppression (GAO 2007; GAO 2009; Stephens *et al.* 2013). Since most dry forests of the United States were historically prone to frequent, low intensity fires, fuel treatments have emerged as a potential supplement to suppression (Allen *et al.* 2002; Graham *et al*. 2004; GAO 2007; Fulé *et al*. 2013).

While direct effects of wildfires on vegetation are often the focus of public attention, post-fire flooding and erosion can be one of the most damaging effects wildfires can have on the landscape. Peak discharge can increase following a fire for a variety of reasons, while water yield may increase but less dramatically (Anderson *et al.* 1976; Canfield *et al.* 2005; Moody *et al.* 2013). Vegetation cover is greatly reduced and hydrophobic soils can form, causing decreased interception and infiltration which lead to an increase in runoff and erosion during a precipitation event (Robichaud *et al.* 2000; DeBano *et al.* 2003).

There is evidence that pre-wildfire fuel treatments can indirectly mitigate post-fire runoff and erosion (Anderson *et al.* 1976; Wohlgemuth *et al.* 1999; Loomis *et al.* 2003; Meixner and Wohlgemuth 2004). If fuel treatments can be successful in reducing post-fire runoff and erosion by moderating fire severity, this may be a more cost-effective solution than spending large sums fighting wildfires and then mitigating high fire severity areas after the wildfire occurs to prevent flooding and severe erosion.

Although fuel treatments can take many forms, the most common types used on public lands are prescribed fire and mechanical thinning (GAO 2007). Prescribed burning is used to facilitate the reintroduction of fire into an ecosystem in a way that can be controlled and limited in fire intensity. Mechanical thinning involves removal of understory trees, spreading surface fuels, and thinning the crown layer in order to lessen the load and continuity of fuels in a forest. Both methods have proven to be locally successful in reducing the intensity of wildfires, with concomitant reductions in fire severity (Agee and Skinner 2005; Martinson and Omi 2013; Kennedy and Johnson 2014). However, despite large increases in investment into fuel treatments, the amount of treated area within forests in the United States is still not sufficient to limit fire severity on a large scale (North *et al.* 2012). Scientists have recommended treating even larger areas in the future, which may increase the role of fuel treatments in national fire policy (Stephens *et al.* 2013).

Modeling fuel treatments, wildfire, and post-fire hydrological response

Models can help land managers simulate and visualize the effects of treatments, and their potential impacts on fire severity and post-fire hydrological response. One non-spatial model that simulates fuel treatments is FuelCalc, which calculates initial forest fuel characteristics from forest inventory data and allows users to select specific treatments to apply to a particular stand. It then outputs post-treatment fuel characteristics, which can then be input into fire simulation models if desired (Heward *et al.* 2013).

The most widely used fire effects model is the First Order Fire Effects Model (FOFEM). FOFEM uses fire behavior inputs along with forest inventory data, including tree density, species, tree height, diameter-at-breast-height (DBH), and canopy class, to model tree mortality, fuel consumption, smoke emissions, and soil heating (Reinhardt 2003; Lutes 2013). The Wildland Fire Assessment Tool (WFAT) couples and runs FOFEM and FlamMap, a fire behavior model, in a GIS format. WFAT requires users to supply the raster layers needed to run FlamMap along with a layer of tree characteristics needed in FOFEM to model fire effects. The tool runs FlamMap to obtain the necessary fire behavior inputs for FOFEM before running FOFEM and FuelCalc (Tirmenstein *et al.* 2012).

Several models exist to predict the impacts of post-fire runoff and erosion. The Water Erosion Prediction Project (WEPP) is a process-based model that focuses on erosion processes for single hillslopes and small watersheds (Larsen and MacDonald 2007). The Erosion Risk Management Tool (ERMiT) is an erosion-prediction tool widely used for post-fire modeling, allowing for the determination of sediment yield probabilities at the hillslope level (Robichaud *et al.* 2007). The tool uses WEPP to provide these probabilities based on variability in weather, fire effects, and distribution of fire severity (Robichaud *et al.* 2007).

Although the above models are useful for predicting post-fire erosion at a hillslope or small watershed scale (< 1km^2), a model that can treat larger watersheds and predict runoff and erosion across several scales (hillslope to large watershed) would be a useful planning tool. The Kinematic Runoff and Erosion Model (KINEROS2) is a physically-based event-driven hydrological model that is usable in a GIS interface by its inclusion in the Automated Geospatial Watershed Assessment Tool (AGWA; Semmens *et al.* 2007; Goodrich *et al.* 2012). AGWA incorporates KINEROS2 into GIS by automating certain processes and running the model on all hillslopes and channels within a delineated watershed.

While these models are all used independently, there is currently no method that couples them to predict how pre-wildfire fuel treatments impact post-wildfire hydrological effects. Linked or coupled models are used widely in ecology, where no single platform is likely to be adequate to address all potential research applications (Foley *et al*. 1998). Such a modeling approach is outlined in this study, linking FuelCalc, FOFEM, and KINEROS2 in order to give land managers a way to model planned fuel treatments, wildfire, and post-fire hydrological impacts together (Fig. 1). We demonstrate this modeling approach in case studies at Zion (ZION) and Bryce Canyon (BRCA) National Parks.

Methods

Study sites

Zion and Bryce Canyon National Parks are located in southwestern Utah, USA, within the Temperate Desert Mountains ecoregion as defined by Malamud *et al.* (2005). In Southwestern Utah, most fires occur during the hot, dry summer months which are followed by late summer monsoon thunderstorms (National Park Service 2004). Both Parks are within the Arizona rainfall type with the medium intensity condition defined by Moody and Martin (2009), having a 2-year, 30-minute rainfall intensity of 20-36 mm hr^{-1}. The hydro-geomorphic regime of Zion National Park is characterized by steep slopes and easily eroded soils. Bedrock/slickrock exposures are common (National Park Service 2004). Deep, narrow slot canyons can carry rapid flash floods as a result of these conditions. Bryce Canyon is characterized by a forested plateau above cliffs and tower formations of exposed sandstones and shales. These formations are very steep and highly erodible, which can lead to large sediment yields during rain events (Kelletat 1985; Doremus and Kreamer 2000).

The modeled watershed in Zion includes Wildcat Canyon at the north edge of the Park, which drains into the Right Fork of North Creek (Fig. 2). The outlet of the watershed is within a slot canyon in North Creek about 2.5 kilometers downstream from the outlet of Wildcat Canyon. The watershed is 2,297 hectares in area, with elevations ranging from 1,704 to 2,492 meters above sea level. This watershed was selected for study because it includes the location of a planned prescribed burn. The burn area is in the northern section of the watershed and includes about 460 hectares (about 20% of the watershed) of mixed forest types including white fir (*Abies concolor*), pinyon/juniper (*Pinus monophylla* and *edulis/Juniperus osteosperma*), quaking aspen (*Populus tremuloides*), ponderosa pine (*Pinus ponderosa*), and gamble oak (*Quercus gambelii*; Zion National Park 2009). Much of the area's current forest conditions are more overgrown than historical conditions, due to more than a century of fire suppression efforts (National Park Service 2004). The Park's goals for the prescribed fire include limiting fire spread into the Wildland Urban Interface, improving vegetation species diversity, and providing benefits to wildlife (Zion National Park 2009).

The modeled watershed in Bryce Canyon is at the southern end of the Park near Rainbow Point lookout (Fig 2). The watershed outlet is at the Park boundary and it drains into Willis Creek, part of the larger Paria River watershed. The watershed is 216 hectares in area, and ranges in elevation between 2,306 and 2,778 meters above sea level. Park staff have identified 12.51 hectares of the upper part of this watershed (about 6% of the entire watershed) for a mechanical thinning treatment. The treatment area is above the plateau rim and includes thick, mixed conifer forest. The Park's goal for the thinning project is to reduce hazardous fuels that would support extreme fire behavior in and around heavily-visited areas that contain several historical structures (Brothwell 2012).

Modeling fuel treatments

Prescribed fire at Zion

WFAT was used to simulate the prescribed fire in Wildcat Canyon in Zion. The spatial topography and fuel input layers necessary to run the model were obtained from LANDFIRE (LF; available at http://www.landfire.gov/; Rollins, 2009). Fuel inputs included canopy base height, canopy bulk density, canopy cover, and canopy height, fire behavior fuel model (FBFM), and fire effects fuel model (FEFM). The National Tree List Layer (NTLL) was also used as an input into WFAT. NTLL contains the information necessary for FOFEM to calculate tree mortality (Drury and Herynk 2011). The NTLL makes use of the LF-Reference Database, a database of geo-referenced field data for forest fuels used to compile LF layers within the United States.

Weather conditions for the prescribed fire were set according to the Weather and Fuel Guidance Parameters, as specified by the desired prescribed fire intensity conditions in the Wildcat Prescribed Burn Plan (Table 1; Zion National Park 2009). To input these weather conditions in WFAT, fixed fuel moisture files were created and used for the fire simulation (Tirmenstein *et al.* 2012). Fuel moistures from the Burn Plan for 1-hour, 10-hour, 100-hour, live herbaceous, and live woody fuels were used.

After the prescribed burn was simulated using existing fuels, WFAT input layers were altered to represent the treated landscape. The input layers obtained from LF were altered or 'treated' by WFAT in the prescribed burn simulations automatically, and were output by the tool. Preparing the tree list layer for wildfire simulation required manual alterations since a treated tree list layer is not an output of WFAT. This required manipulating the tree list database outside the GIS interface using the percent mortality output layer from the WFAT prescribed burn simulation, which provided the percent of trees killed within each cell. In order to remove all the killed trees from the tree lists, enough trees were removed from each tree list to match the percent mortality value for that cell. To select which trees to remove from the tree lists for cells that experienced partial mortality, it was assumed that the prescribed fire killed the smallest diameter trees first. This assumption is supported by multiple studies that have shown DBH to be negatively correlated to tree mortality, especially when used as a surrogate for bark thickness and canopy height (Harrington 1987; Ryan and Reinhardt 1988; Stephens and Finney 2002; Hull Sieg *et al.* 2006).

Mechanical thinning at Bryce Canyon

Since WFAT did not include the mechanical thinning functionality of FuelCalc at the time of this study, tree list manipulation and the stand-alone non-spatial version of FuelCalc were used to model the planned mechanical treatment at Bryce Canyon. Tree lists from NTLL were input into the model, which calculated pre-treatment stand measurements corresponding to LF layers for canopy bulk density, canopy base height, canopy cover, and FBFM. The mechanical thinning treatment applied was a simplified version of the methods described in the Rainbow Point Mechanical Fuel Reduction Plan (Brothwell 2012). This involved altering, or 'thinning' all tree lists that had >40 stems per hectare to below that threshold, deleting from the tree lists all the smallest trees with a diameter at breast height of <20.3 cm (8 in) first. Once this treatment was applied, the treated tree lists were placed back into FuelCalc to calculate post-treatment stand characteristics.

Modeling wildfire with WFAT

In order to evaluate the effect of fuel treatments on wildfire severity, we modeled wildfires on both untreated and treated landscapes. Wildfires on the untreated landscapes in both Parks used unaltered LF 2008 and NTLL layers for spatial inputs into WFAT. For the wildfire on the treated landscape in Zion, the output layers from WFAT following the prescribed fire simulation and the manually-altered NTLL tree lists were used. For the wildfire on the treated landscape in Bryce Canyon, the LF layers needed to be altered manually since the mechanical thinning treatment couldn’t be simulated within WFAT. FuelCalc calculates values such as canopy bulk density and canopy base height directly from the input tree list. Since these values are also available from LF layers, it was possible to compare the calculated stand measurement values in FuelCalc from NTLL with those from LF. However, the pre-treatment stand measurement values derived from the NTLL tree lists in FuelCalc did not always match the values from the LF layers in the same location. Therefore, post-treatment stand measurement values could not be derived directly from the FuelCalc results to create post-treatment spatial layers. Instead, the percent change from the pre- to post-treatment stand measurements recorded by FuelCalc from the NTLL tree lists was applied to the pre-treatment LF layers to obtain spatial post-treatment layers. These created layers, along with the treated NTLL tree lists, were input into WFAT to model wildfire on a treated landscape.

All simulated wildfires were based on the weather conditions directly preceding recent wildfires at the two Parks. For Zion, conditions preceding and during the 2006 Kolob Fire were used (National Park Service 2006). For Bryce Canyon, conditions for the 2009 Bridge Fire were used. In order to best represent the conditions in the study area preceding these fires, weather parameters were obtained from Remote Automated Weather Stations near the wildfire locations (Lava Point for Zion, Aqua Canyon for Bryce Canyon). WFAT allows fuel moistures to be 'conditioned' by weather variables preceding the simulated fire (Tirmenstein *et al.* 2012), which was done for the wildfires in this study. Conditioning variables included the daily precipitation totals, high and low temperatures, relative humidity percentages, and wind characteristics for the five days preceding the two fires.

Two wildfires were modeled at each Park: one covering the entire watershed, and another covering only the upper portion of the watershed (which in both cases included all of the treated area).

Modeling post-fire runoff and erosion with AGWA

The KINEROS2 model within AGWA was used to model all rainfall events in this study. Spatial inputs into AGWA included 10x10 meter digital elevation models (DEMs) from the United States Geological Survey's (USGS) National Map (available at http://nationalmap.gov/viewer.html), STATSGO soil layers (available at http://soildatamart.nrcs.usda.gov/), and Park vegetation maps modified to fit National Land Cover Database classifications (available at http://www.usgs.gov/core_science_systems/csas/vip/index.html). AGWA alters KINEROS2 input parameters (Manning's *n* roughness coefficient, saturated hydraulic conductivity, and interception) to represent a post-fire landscape by altering land cover based on burn severity (Canfield *et al.* 2005; Burns 2013). The Keane Severity Index (KSI) output from WFAT was used to create the fire severity layer used by AGWA to alter land cover values. KSI uses three fire effects outputs from FOFEM to create fire severity classes of low, moderate, and high. Metrics include soil heating, tree mortality, and fuel consumption (Keane *et al.* 2010). KSI is used as an index of fire severity in this study since it is a built-in output in WFAT and corresponds well with the definition of fire severity from Keeley (2009) as the loss of organic matter from aboveground and belowground sources. All references to "fire severity" in this study relating to WFAT outputs refer to the KSI directly.

At both study sites, rainfall events were modeled on three landscapes for each of the two wildfire scenarios: untreated and unburned, untreated and burned by wildfire, and treated and burned by wildfire. 2-year 30-min design storms were modeled on both sites to match typical monsoonal rains of southern Utah (13.6 mm rainfall depth in 30 min at Zion, 11.9 mm rainfall depth at Bryce Canyon). The 2-year 30-min storm has been suggested as an appropriate metric to use when examining post-fire hydrologic responses, since post-fire runoff and erosion can be significant even at low return intervals and short durations (Moody *et al.* 2013). The depth and durations of these storms were obtained from the online NOAA Atlas 14 point precipitation frequency estimates (National Oceanic and Atmospheric Administration 2013) using coordinates of the centroids of the watersheds. The storm was applied uniformly over the entire watershed using a SCS Type II intensity distribution built into AGWA (Burns 2013). While monsoonal thunderstorms are typically not spatially uniform over watersheds of this size (Goodrich *et al.* 2008), this assumption treats the entire watershed equally from the perspective of rainfall inputs. This enables Park managers to focus on assessing the effects of treatments and wildfires without the compounding complication of storm location and movement. The implications of this assumption are explored in more detail in another study in this special issue (Sidman *et al.* 2014).

Results/Discussion

Fuel treatments

Both modeled fuel treatments clearly changed stand characteristics within the treatment areas (Fig. 3). The prescribed burn at Zion affected a wide range of characteristics, altering canopy base height, canopy cover, canopy bulk density, and tree density, and changing the canopy height and fuel loading models (FLM) in some areas. Mechanical thinning at Bryce Canyon did not change canopy height or FLM, since by design, the treatment did not remove any large trees that control the canopy height, and did not remove or add any ground fuels. Another difference between the two treatments was that the prescribed burn (Zion) increased areas of non-forested land, while the mechanical thinning (Bryce) did not. This is because the prescribed burn consumed all trees in some areas, rendering them non-forested by the model. The mechanical thinning, however, reduced only tree density, never removing all the trees from an originally forested area.

The untreated landscape in Bryce Canyon had a higher percentage of area with denser forest than Zion: 91% of Bryce Canyon's treatment area had canopy base heights of 0-0.9 meters, and 87% had more than 300 trees per hectare (Fig. 3). Bryce Canyon's mechanical thinning was focused on reducing the density in those denser areas, while ignoring the less-dense areas. The post-treatment landscape represents this aim. The mechanical thinning reduced areas with a canopy base height of 0-0.9 meters down to 45% of the total treatment area, and removed all area with more than 300 trees per hectare. It also reduced area with a canopy bulk density of equal to or greater than 0.10 kg m^{-3} from 34% pre-treatment to only 12% post-treatment.

Zion's treatment area had lower initial forest density. Only 20% of the area had canopy base heights of 0-0.9 meters and 50% of the area had more than 300 trees per hectare. The prescribed burn influenced the treatment area more uniformly than the mechanical thinning, affecting both the dense and sparse areas. The burn reduced areas with a canopy base height of 0-0.9 meters from 20% to 10% of the treatment area, and areas of 1.0-1.9 meters from 25% to 17%. Prescribed fire did not completely eliminate areas with over 300 trees per hectare, reducing those areas from 50% to 33%. Yet the increase in non-forested land shows that some of the sparser areas were burned and some dense areas burned with high intensity. 96% of the prescribed burn area with less than 150 trees per hectare resulted in at least low burn severity, while about 20% of areas with more than 300 trees per hectare resulted in high burn severity.

Wildfire

The two fuel treatments had different impacts on subsequent wildfires that burned over the areas in which they were implemented (Fig. 4). The prescribed burn increased the watershed's unburned area in both the entire watershed wildfire (3% increase) and the upper watershed wildfire (24% increase), whereas the mechanical thinning did not change unburned area at all (Table 2). This can be attributed to the fact that the prescribed fire completely consumed some areas of forest, rendering them unburnable by the wildfire. This was not the case for the mechanical thinning, which simply reduced stand density. The prescribed burn was more effective than the mechanical thinning at reducing high severity area for both wildfire scenarios, but the mechanical thinning did more to reduce moderate severity area in both wildfire scenarios. The larger decrease in high severity area caused by the prescribed burn is likely due to some of the high severity area in the untreated scenario becoming unburned in the treated scenario since it was burned at high severity during the prescribed fire.

By virtue of the ratios of treatment areas to wildfire sizes, the fuel treatments had less impact on the entire watershed wildfire than on the upper watershed wildfire. The prescribed fire reduced high severity in the entire watershed wildfire (20% treatment area/wildfire area) by 22%, whereas it was reduced by 39% in the upper watershed wildfire (45% treatment area/wildfire area). Similarly, the mechanical thinning reduced high severity in the entire watershed wildfire (5.9% treatment area/wildfire area) by 5% and in the upper watershed wildfire (45% treatment/wildfire area) by 29%. This is because the treatment areas make up a larger portion of the upper watershed wildfire areas than the entire watershed wildfire areas, increasing the impact of the treatments. Because of the random nature of wildfire ignition location and weather conditions, it is impossible to choose a 'best' or 'most realistic' wildfire extent when running WFAT. The comparison in this study of differing wildfire sizes simply points to the importance of modeling different sized fires in order to gain a better understanding of the range of outcomes that are possible in a given area.

Post-wildfire hydrological response

In the entire-watershed wildfire scenarios, fuel treatments had a larger impact on stream reaches just downstream of the treatment areas than at the watershed outlets (Fig. 5). In Zion's Wildcat Canyon just below the treatment area, the prescribed fire reduced peak flow by 7% while change was negligible in the slot canyon at the watershed's outlet (Fig. 6; Table 3). In Bryce Canyon peak flow was reduced by 34% at a trail crossing just below the mechanical thinning area, while the change was also negligible at the watershed outlet at the Park boundary. The results from the upper-watershed wildfire scenarios showed a slightly different pattern (Fig. 7; Table 3). In Zion, the prescribed fire reduced peak flow by 9% at both Wildcat Canyon and the slot canyon. However, in Bryce Canyon, the prescribed fire reduced peak flow by 50% at the trail crossing but did nothing at the park boundary.

The lack of impact at the watershed outlets for both study sites points to both the importance of treatment size and treatment location. Firstly, the treatments in both sites covered relatively small portions of the entire watersheds, effectively limiting the impacts of the treatments at the watershed outlet. Too large a percentage of the watersheds were untreated for the treatment to show any substantial impact. Secondly, although total volume and sediment should not be significantly impacted by treatment location, the locations of the treatments were too far upstream to impact the peak flows at the outlets. Rain that fell on the upper watersheds in both sites, including the treatment areas, did not reach the outlets until the recession limbs of the hydrographs. To have a larger impact on peak flow, treatment areas would have to be relocated to the centers or lower portions of the watersheds.

At the location directly below the Bryce Canyon treatment area, mechanical thinning reduced peak flow by a greater percentage than the prescribed burn. This difference may be due to the lower rainfall total and maximum rainfall intensity exhibited by the event at Bryce Canyon. Percent change tends to be accentuated at lower absolute values, so a slight absolute change may appear as a large relative change. In absolute terms, the prescribed burn reduced peak flow by 0.23 $m^3 s^{-1}$ below the treatment area, while the mechanical thinning reduced it by only 0.0023 $m^3 s^{-1}$.

Caveats of the modeling approach

Despite the success of developing this modeling approach linking fuel treatments to post-fire runoff and erosion, several limitations and sources of error exist. One is the variable quality of input data. For example, the level of detail included in NTLL (complete stands for the entire contiguous United States), combined with this layer's integral role in determining tree mortality, make the accuracy of this layer critical to this modeling approach due to the sensitivity of KINEROS2/AGWA to fire severity. However, precision testing done by Drury and Herynk (2011) indicated that only 27% of pixels matched the dominant species of independent field plots at their study location. Furthermore, it is unknown if NTLL will ever be updated in the manner of LF to provide current data. Given these deficiencies, it would be preferable to utilize local tree list data in lieu of the NTLL if available. Still, in the absence of local data containing all the necessary parameters to run FOFEM, NTLL is currently the best default alternative on a national scale. In addition, recent studies have explored the option of classifying fuels through use of Light Detection and Ranging (LiDAR). Airborne LiDAR scanners may be a more accurate way to classify fuel characteristics such as canopy height, canopy bulk density, and canopy base height (Erdody and Moskal 2010). LiDAR may also have the capability of providing complete and accurate tree lists over entire landscapes (Van Leeuwen and Nieuwenhuis 2010; Swetnam and Falk 2014).

The assumption made in this modeling approach that smaller trees have higher differential mortality, is another possible source of error. This assumption is simplistic, since bark thickness, crown base height, tree species, tree vigor, and fire behavior all play a role in tree mortality (Ryan and Reinhardt 1988; Lutes 2013; van Mantgem *et al*. 2013a, b). However, the assumption was made for this modeling methodology to limit the approach's complexity.

Another source of error within the KINEROS2/AGWA model comes from the alterations AGWA makes to KINEROS2 input parameters based on fire severity. Currently, AGWA modifies only the land cover input layer, changing percent cover and hydraulic roughness as a function of the level of burn severity. Interception is altered as a function of canopy cover change. Hydraulic conductivity is altered solely based on the drop in percent cover based on results from rainfall simulation experiments conducted under a variety of cover conditions (Goodrich 1990). Hydrophobicity, ash residue and impacts of the collapse of soil structures on hydraulic conductivity are not considered, as this information is not available from the non-field verified Burned Area Reflectance Classification (BARC; DeBano *et al.* 1998; Moody *et al.* 2013). Ideally, field or remotely sensed indicators of hydrophobicity, ash accumulation and soil structure change could be incorporated into AGWA to further refine post-fire soil parameter estimates. During 2014 BAER deployments, post-fire field observations have been used to modify hydrologic conductivity infiltration parameters in AGWA simulations that were initially based solely on the non-field verified BARC maps. Furthermore, the parameter changes selected for KINEROS2 inputs are based only on one post-fire watershed in New Mexico (Canfield *et al.* 2005). Parameter changes could vary in different locations with fires of different severities and watersheds with different characteristics. Current efforts are underway to identify and collect high-quality rainfall, runoff, and if available, sediment observations from watersheds prior to, and after fire, to add to the analysis presented in Canfield *et al.* (2005) to determine more robust rules for altering post-fire model parameters. If remote sensing methods could reliably estimate areas of hydrophobicity and significant ash residue, more informed methods to alter post-fire KINEROS2 model estimate using this information would be warranted.

Implications for use by land managers

The first step in deciding if this modeling approach is viable for use by land managers is to verify the accuracy of modeled results. The accuracy of the results from FOFEM/WFAT was determined by comparing the KSI severity distribution of the untreated wildfires to the burn severity distributions of the actual wildfires they were designed to emulate (Table 4). The burn severity distributions of the actual wildfires were obtained from the Monitoring Trends in Burn Severity (MTBS) database, which relies heavily on satellite imagery to classify burn severity. Therefore, it is inherently different than the KSI used by WFAT, but comparing the two can still be useful for analyzing how well FOFEM/WFAT matches actual wildfires. The untreated entire watershed wildfire at Zion matched the severity distribution of the Kolob Fire very closely, having the same amount of unburned and high severity area, while underestimating moderate severity and overestimating low severity by 5%. The untreated entire watershed wildfire at Bryce

Canyon did not match the severity distribution from the Bridge Fire quite as well; the modeled fire overestimated moderate severity by 18% and underestimated high severity by 15%. Still, the unburned and low severity of the modeled fire at Bryce Canyon were within 4% of the Bridge Fire properties. Considering that weather inputs from the Kolob and Bridge fires were used for the model wildfires at Zion and Bryce Canyon, it is encouraging to observe that the severity distributions of the two modeled wildfires match those of the actual wildfires relatively well.

To determine the accuracy of post-fire peak discharge modeled by KINEROS2/AGWA, the change from pre- to post-fire peak discharge modeled by KINEROS2/AGWA in this study can be compared to measured increases from actual pre- and post-fire flood events. Neary *et al*. (2005) recorded several such events, in which post-fire peak discharges increased by a factor of 1.4x to 2,232x in the western United States. Untreated post-fire peak discharges recorded in this study increased from pre-fire peak discharge by factors ranging between two and 79. In order to compare KINEROS2/AGWA modeled sediment yield, results can be compared to total storm sediment yields reported by Robichaud *et al.* (2008). That study observed post-fire sediment yields between 0 and 19.8 Mg ha^{-1}. Storm total sediment yields in this study ranged between 0.005- 1.81 Mg ha^{-1}. Although this comparison is limited by the differing study site locations and fire severity distributions, it shows that modeled sediment yields were within a realistic range.

Almost no studies have attempted to determine the change in runoff and erosion from wildfire on an untreated to a treated landscape. A significant obstacle to completing a study of this nature is the limited availability of high-resolution rainfall observations, which are essential to validating this approach. Although Wohlgemuth *et al.* (1999) provides such an opportunity, the results mentioned are longer-term sediment yields, rather than event-based yields. This makes it impossible to compare those results with KINEROS2 results. However, this study's results are consistent with the general trends observed: fuel treatments mitigated wildfire severity and therefore post-fire runoff and erosion.

There are many potential uses of this linked modeling approach. Land managers could use these tools to decide which fuel treatments or combination of treatments lower post-wildfire runoff and erosion down to an acceptable threshold. This would allow them to better protect values at risk downstream of potential wildfire locations. Given the limitations noted above it is best currently to use the modeling approach to spatially compare the relative change of various scenarios in an attempt to identify the best fuel treatment type and its location. If multiple locations are being considered for fuel treatments, scenarios could be evaluated with this modeling approach to determine the best locations to meet management objectives and prioritize where fuel treatments should be placed.

Conclusion

The modeling approach described in this study provides a viable option for landscape scientists, watershed hydrologists, and land managers hoping to predict the impact of fuel treatments on post-wildfire runoff and erosion, despite several limitations and potential sources of error. Several uses of the model exist, from measuring how well treatments mitigate the hydrologic response following wildfire, to determining the best spatial location of the treatments. It is recommended that the modeling approach be used as a relative change tool, rather than a tool to predict absolute values of peak flow and sediment yield.

The results of the case studies employed here suggest that the magnitude of the effect of a fuel treatment on post-wildfire hydrological response mitigation varies according to several factors, including the size of the wildfire and the size of the fuel treatment. It was not the objective of this case study to decide whether or not the proposed fuel treatments in Zion and Bryce Canyon National Parks were worthwhile management options or under what circumstances they should be implemented. This is especially true since the main goals of Park staff in both cases were to reduce fire behavior and improve forest health, not to mitigate post-fire hydrological response. This study aimed primarily to demonstrate a novel linked model approach, and secondarily to give Park managers more information and data to make a more-informed management decision.

Several items should be addressed to further streamline this modeling approach and reduce potential limitations and error. Within the WFAT framework, the most important area to address is the creation of a publicly available national tree list layer. The functionality of the tree list database could be improved as well to include automated updates to account for the changes caused by fuel treatments. Better ways to map forest fuel characteristics on a landscape level must be explored as well, such as the use of LiDAR.

Within the AGWA framework, post-fire alterations of KINEROS2 inputs should be further researched. Parameter changes should be made according to relationships that are drawn from a larger number of actual wildfires and should include further soil alterations due to ash, hydrophobicity and soil structure change. This would decrease potential sources of error in hydrological modeling and increase model sensitivity to wildfire effects.

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Table 1. WFAT Input weather parameters for modeled prescribed fires. Values come from the Wildcat Prescribed Burn Plan (National Park Service, 2009).

Parameter	Value
Relative Humidity (%)	20
6m Windspeed (ms^{-1})	4.47
Wind Direction (degrees)	247
1-hr fuel moisture (%)	6
10-hr fuel moisture (%)	6
100-hr fuel moisture (%)	10
Woody Live fuel moisture (%)	80
Herbaceous Live fuel moisture (%)	80

Table 2. Comparison of fire severity (KSI) between wildfires on untreated and treated landscapes.

	Entire Watershed Wildfire					
	ZION (2297 ha)			**BRCA (216 ha)**		
KSI	**Untreated (ha)**	**Treated (ha)**	**% Change**	**Untreated (ha)**	**Treated (ha)**	**% Change**
Unburned	346.68	356.40	**2.80**	43.83	43.83	**0.00**
Low	935.37	955.35	**2.14**	64.08	66.78	**4.21**
Moderate	827.91	839.25	**1.37**	91.62	89.82	**-1.96**
High	186.84	145.80	**-21.97**	16.65	15.75	**-5.41**
	Upper Watershed Wildfire					
	ZION (1028 ha)			**BRCA (28 ha)**		
	Untreated (ha)	**Treated (ha)**	**% Change**	**Untreated (ha)**	**Treated (ha)**	**% Change**
Unburned	41.13	50.85	**23.63**	2.61	2.61	**0.00**
Low	535.41	555.39	**3.73**	5.04	7.74	**53.57**
Moderate	346.68	358.02	**3.27**	15.84	14.58	**-7.95**
High	105.12	64.08	**-39.04**	4.86	3.42	**-29.63**

Table 3. Results from KINEROS2/AGWA simulations.

Entire Watershed Wildfire				
Prescribed Fire (ZION)				
	Wildcat Canyon		**Slot Canyon**	
	Peak Flow ($m^3 s^{-1}$)	**Sediment ($kg s^{-1}$)**	**Peak Flow ($m^3 s^{-1}$)**	**Sediment ($kg s^{-1}$)**
Untreated, No Wildfire	0.12	21.49	0.97	68.23
Untreated, Wildfire	3.39	1473.61	5.98	804.22
Treated, Wildfire	3.16	1374.11	5.98	804.10
% Change	-6.88	-6.75	0.00	-0.02
Mechanical Thin (BRCA)				
	Trail Crossing		**Park Boundary**	
	Peak Flow ($m^3 s^{-1}$)	**Sediment ($kg s^{-1}$)**	**Peak Flow ($m^3 s^{-1}$)**	**Sediment ($kg s^{-1}$)**
Untreated, No Wildfire	0.000087	0.0012	0.014	0.83
Untreated, Wildfire	0.0067	0.16	0.19	28.63
Treated, Wildfire	0.0044	0.09	0.19	28.63
% Change	-34.46	-44.68	0.00	0.00
Upper Watershed Wildfire				
Prescribed Fire (ZION)				
	Wildcat Canyon		**Slot Canyon**	
	Peak Flow ($m^3 s^{-1}$)	**Sediment ($kg s^{-1}$)**	**Peak Flow ($m^3 s^{-1}$)**	**Sediment ($kg s^{-1}$)**
Untreated, No Wildfire	0.12	21.49	0.97	68.23
Untreated, Wildfire	3.25	1381.76	3.24	324.43
Treated, Wildfire	2.98	1272.44	2.98	293.27
% Change	-8.48	-7.91	-7.98	-9.60
Mechanical Thin (BRCA)				
	Trail Crossing		**Park Boundary**	
	Peak Flow ($m^3 s^{-1}$)	**Sediment ($kg s^{-1}$)**	**Peak Flow ($m^3 s^{-1}$)**	**Sediment ($kg s^{-1}$)**
Untreated, No Wildfire	0.000087	0.0012	0.014	0.83
Untreated, Wildfire	0.0069	0.17	0.029	2.33
Treated, Wildfire	0.0046	0.094	0.029	2.34
% Change	-34.19	-42.99	0.00	0.16

Table 4. Comparison of KSI severity distributions for entire watershed wildfires at ZION and BRCA with the burn severity distributions from the actual wildfires they were meant to emulate. Severity distributions for the Kolob and Bridge fires were obtained from Monitoring Trends in Burn Severity (WLC 2014).

	ZION		**Kolob Wildfire**		**BRCA**		**Bridge Wildfire**	
	ha	**%**	**ha**	**%**	**ha**	**%**	**ha**	**%**
Unburned	347	15%	1,029	15%	44	20%	1,223	24%
Low	935	41%	2,361	34%	64	30%	1,460	29%
Moderate	828	36%	2,857	41%	92	42%	1,212	24%
High	187	8%	643	9%	17	8%	1,170	23%

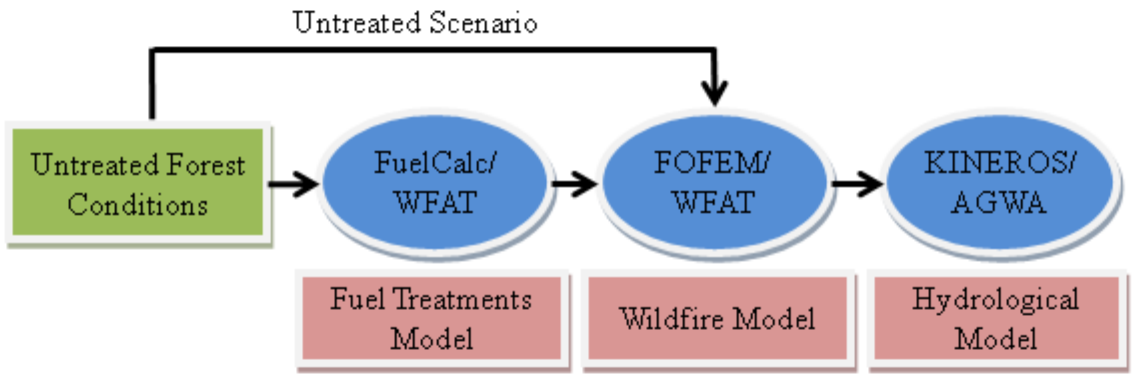


Fig. 1. Modeling process.

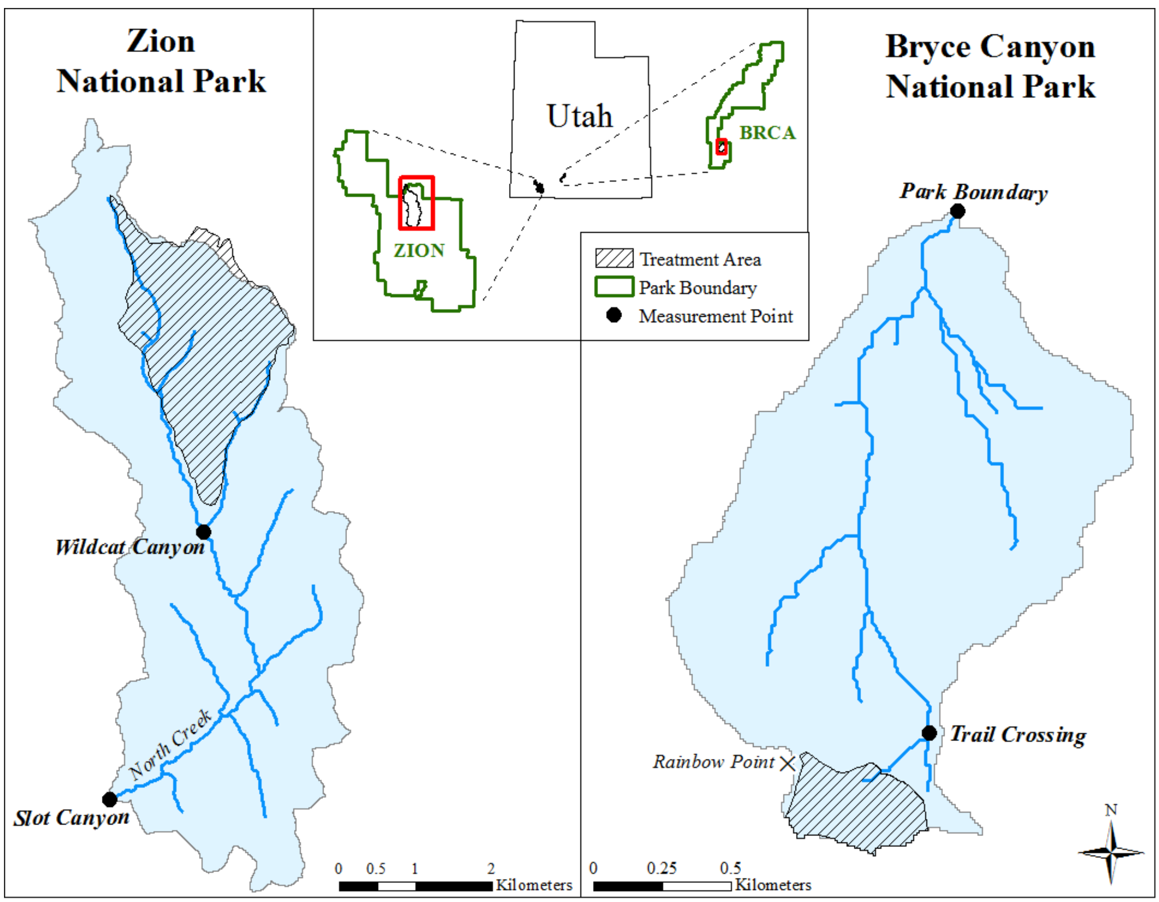


Fig. 2. Location of study sites.

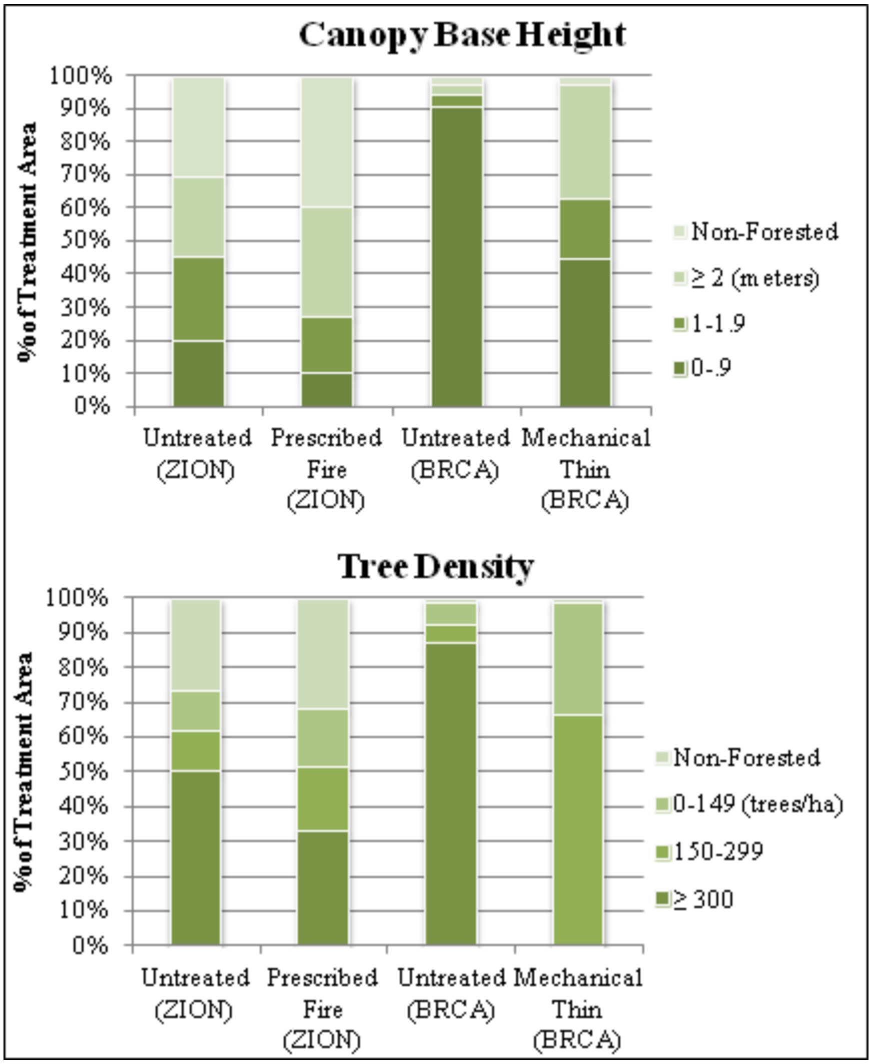
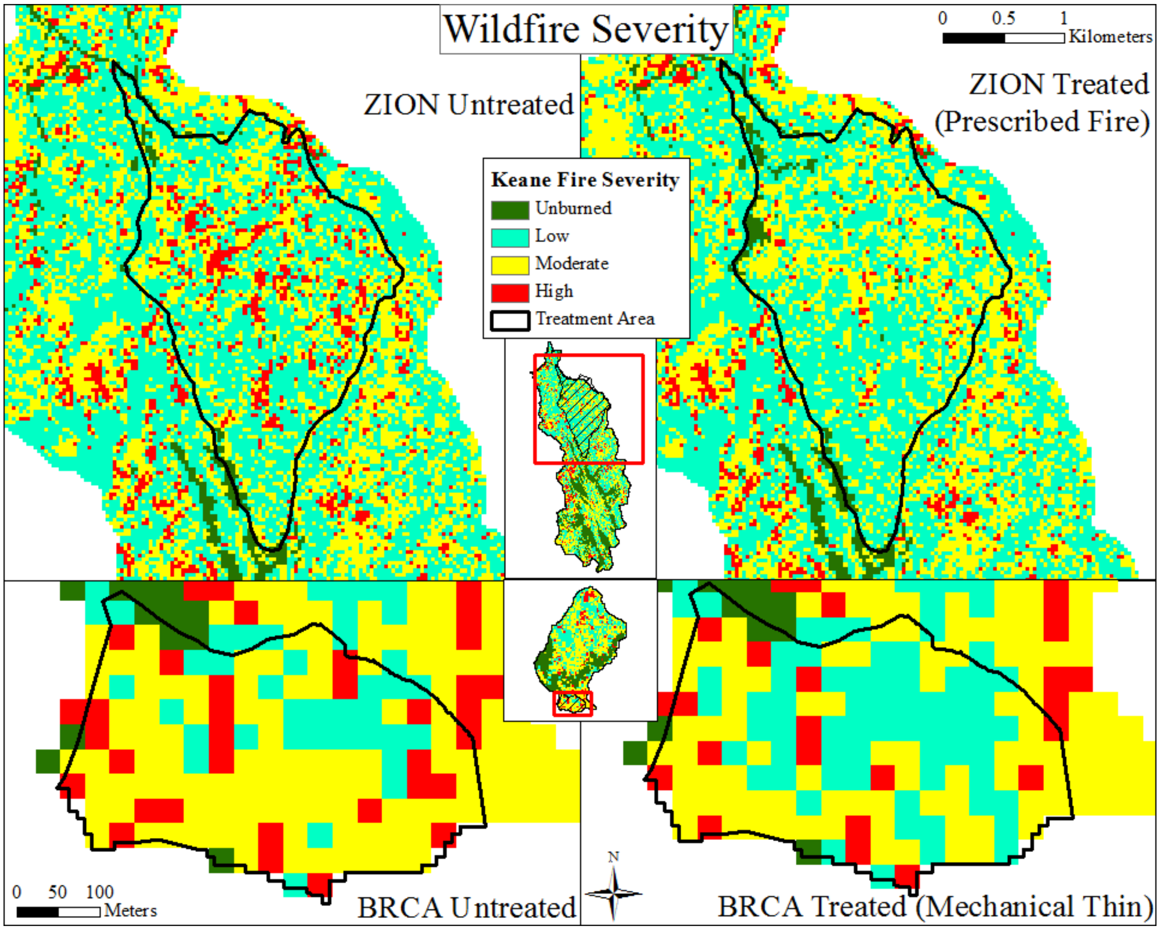


Fig. 3. Comparison of pre- and post-treatment landscapes.

718 

719 Fig. 4. Comparison of entire watershed wildfires on untreated and treated landscapes.

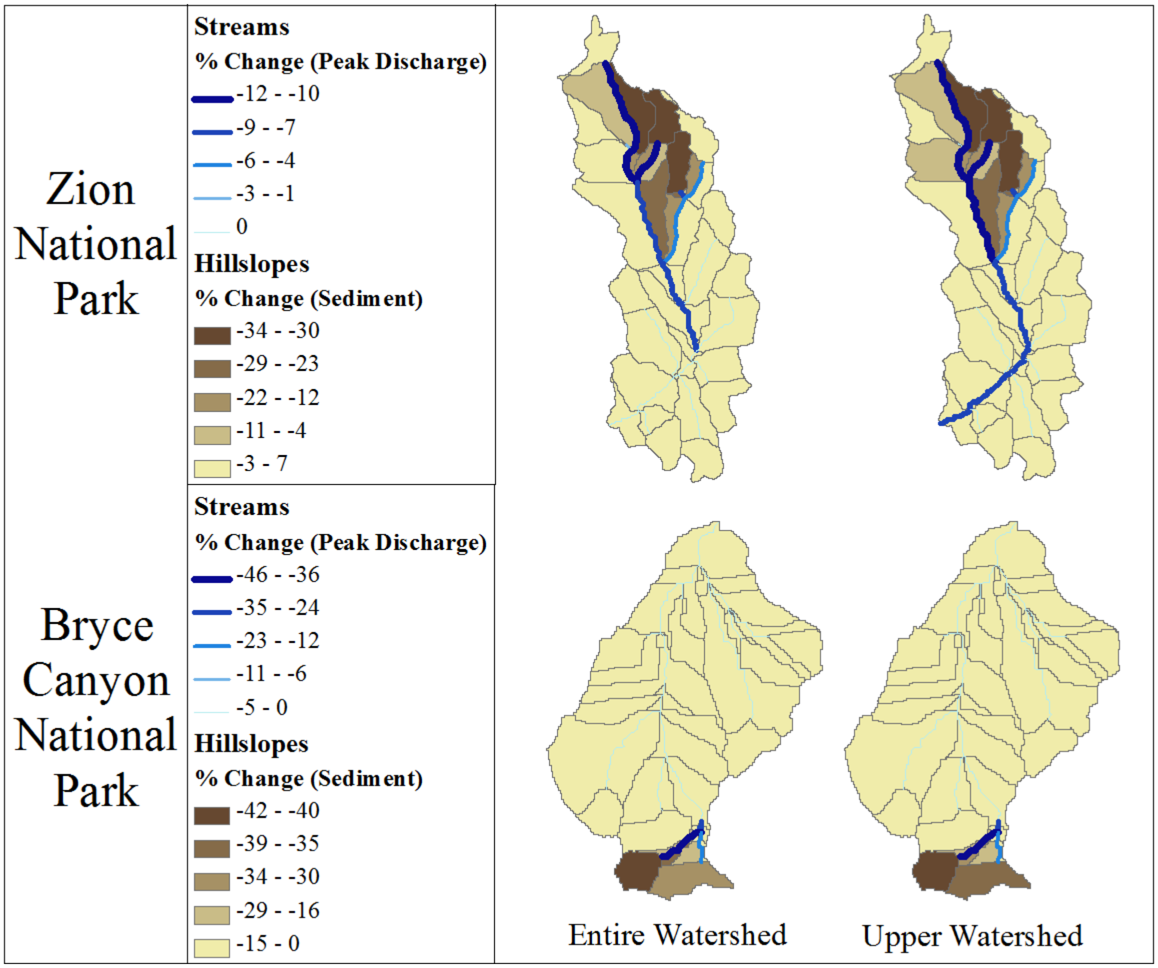


Fig. 5. Comparison of change in hydrological response between untreated and treated landscapes after entire watershed and upper watershed wildfires.

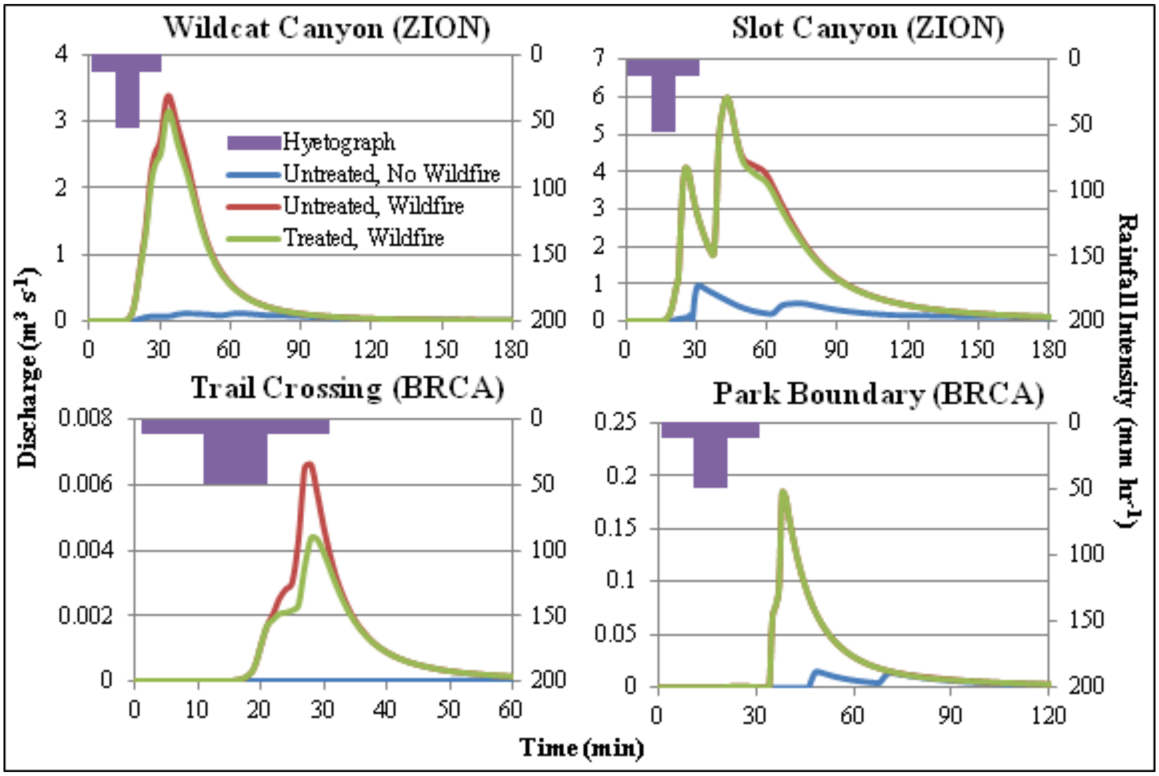


Fig. 6. Hydrographs and hyetographs illustrating design storm rainfall and watershed response after entire watershed wildfires. Hydrographs, which show the discharge over time in a stream channel, correspond to the primary (left side) y-axes. Hyetographs, which show the rainfall intensity over time for the design storms, are inverted and correspond to the secondary (right side) y-axes. Hyetographs are shown as solid to indicate that rainfall was applied continuously throughout the storm.

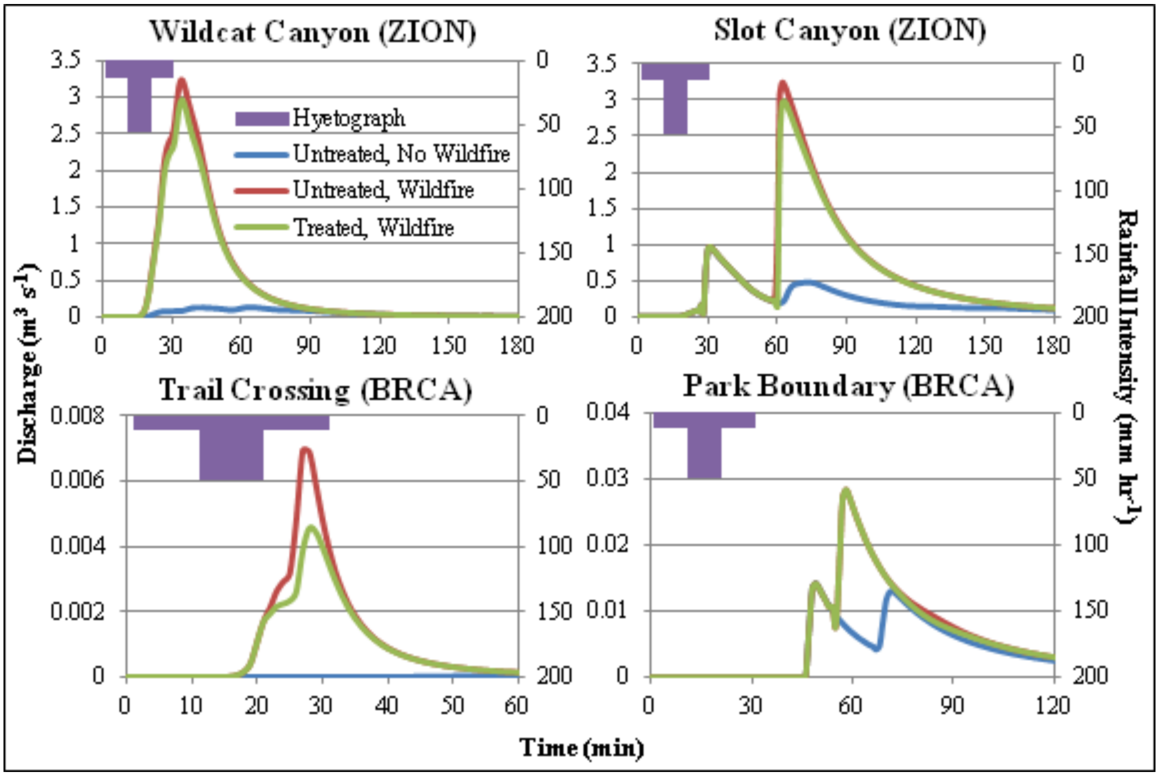


Fig. 7. Hydrographs and hyetographs illustrating design storm rainfall and watershed response after upper watershed wildfires. Hydrographs, which show the discharge over time in a stream channel, correspond to the primary (left side) y-axes. Hyetographs, which show the rainfall intensity over time for the design storms, are inverted and correspond to the secondary (right side) y-axes. Hyetographs are shown as solid to indicate that rainfall was applied continuously throughout the storm.