Effects of wildfire on catchment runoff response: a modelling approach to detect changes in snow-dominated forested catchments

Jan Seibert, Jeffrey J. McDonnell and Richard D. Woodsmith

ABSTRACT

Wildfire is an important disturbance affecting hydrological processes through alteration of vegetation cover and soil characteristics. The effects of fire on hydrological systems at the catchment scale are not well known, largely because site specific data from both before and after wildfire are rare. In this study a modelling approach was employed for change detection analyses of one such dataset to quantify effects of wildfire on catchment hydrology. Data from the Entiat Experimental Forest (Washington State, US) were used, a conceptual runoff model was applied for pre- and post-fire periods and changes were analyzed in three different ways: reconstruction of runoff series, comparison of model parameters and comparison of simulations using parameter sets calibrated to the two different periods. On average, observed post-fire peak flows were 120% higher than those modelled based on pre-fire conditions. For the post-fire period, parameter values for the snow routine indicated deeper snow packs and earlier and more rapid snowmelt. The net effect of the changes in all parameters was largely increased post-fire peak flows. Overall, the analyses show that change detection modelling provides a viable alternative to the paired-watershed approach for analyzing wildfire disturbance effects on runoff dynamics and supports discussions on changes in hydrological processes.

Key words | conceptual runoff model, Entiat, land-cover change, runoff change detection, wildfire

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INTRODUCTION

Research over the past few decades has demonstrated important effects of fire on runoff volume and dynamics. Damage to forest vegetation and the litter layer can reduce interception and evapotransporation, thereby concentrating and increasing the volume of precipitation and snowmelt reaching the soil surface and increasing rainsplash effectiveness. In addition, soil infiltration capacity can be reduced if surface pores are sealed by ash or fine sediment made available by the destruction of soil structure and mobilized by rainsplash, or when fire induces formation of hydrophobic compounds on the soil surface (e.g. DeBano *et al.* 1998; Martin & Moody 2001; Shakesby & Doerr 2006; Sheridan *et al.* 2007). Cumulatively, these effects can increase runoff, peak flow magnitude, flooding, surface erosion, sediment delivery to channels, channel bed and bank erosion, sediment concentration, turbidity and potentially soil mass movements including debris flows (Helvey 1980; Swanson 1981; Johansen *et al.* 2001; Moody & Martin 2001; Conedera *et al.* 2003; Wondzell & King 2003; Lane *et al.* 2006).

While fire effects on hydrology have been clearly demonstrated at the plot scale, the effects on streamflow and sediment movement at the catchment scale are more difficult to quantify (e.g. Burch *et al.* 1989; Booker *et al.* 1993).

doi: 10.2166/nh.2010.036

This is largely because pre-wildfire data are available in only a very few cases (Hoyt & Troxell 1934; Brown 1972; Langford 1976; Campbell *et al.* 1977; Kuczera 1987; Scott & Van Wyk 1990; Lavabre *et al.* 1993; Scott 1993, 1997; Moody & Martin 2001; Lane *et al.* 2006). Furthermore, most studies that have quantified catchment-scale effects have been associated with paired-watershed studies of prescribed fire effects on water quantity and quality. Effects of prescribed fire, while providing useful knowledge, do not directly mimic natural wildfire influences where the magnitude of hydrological change varies over a burned landscape with fire severity (Scott 1993; Moody & Martin 2001; Miller *et al.* 2003). Fire severity, i.e. the magnitude of impacts on vegetation and soil, depends on fire temperature (or fire intensity), duration, spatial extent, and patchiness (DeBano *et al.* 1998; Keeley 2009).

In this study advantage was taken of a rare 'natural' (i.e. not prescribed) fire experiment conducted in the Entiat Experimental Forest (EEF) located in the interior Columbia River basin on the eastern slope of the Cascade Mountains in Washington State, US (Helvey 1980; Woodsmith *et al.* 2004). In this region, fire is an important disturbance process (Hessburg & Agee 2003; Wright & Agee 2004). The planned paired-watershed study became impossible to carry out when the EEF catchments burned unexpectedly on August 24 1970 as part of a 486 km^2 wildfire complex caused by lightning (Helvey *et al.* 1976*a*; Martin *et al.* 1976). At the time of the fire, runoff and other variables had been measured for about 10 years. Following the fire, data recording continued for 7 years until 1977 (Helvey *et al.* 1976*b*; Helvey 1980).

While several studies have examined different aspects of catchment behaviour following the fire in the EEF (Helvey 1974; Helvey *et al.* 1976*a*; Martin *et al.* 1976; Helvey & Fowler 1999), quantifying runoff response changes has been difficult because the control watershed at EEF also burned. Helvey (1980) related the flow response at the burned EEF, Burns Creek catchment (5 km^2) to the nearby, but much larger, Chelan River watershed (2,400 km^2), and found that observed annual runoff for Burns Creek was 100–500 mm larger than runoff predicted using the Chelan River as a control watershed. However, to date, no studies have been able to fully capitalize on the EEF flow data to show how the wildfire altered the runoff response and how the flow response recovered following fire.

This paper presents a change detection modelling approach to examine how wildfire at the EEF changes hydrologic response relative to pre-fire conditions. While modelling approaches to detect changes are generally straightforward (Kuczera 1987; Kundzewicz & Robson 2004) their use is not widespread, particularly for assessment of fire effects. Andréassian *et al.* (2003) and Seibert & McDonnell (2010) have used runoff models to detect gradual changes in watershed behaviour in response to timber harvesting activities. Brandt *et al.* (1988) have used the HBV (Hydrologiska Byråns Vattenavdelning) model (the model employed in these analyses of the EEF data) to quantify clear-cutting effects on streamflow.

The authors are aware of only one study that has applied such a methodology to quantify wildfire effects on catchment hydrology. Lavabre *et al.* (1993) calibrated simple two- and three-parameter models to pre-fire data and used the model to reconstruct the runoff that would have been observed if there had not been any fire. They found an approximately 30% increase in observed water yield relative to this reconstructed streamflow for the first year following the wildfire. They analyzed the same data using a paired-watershed approach, but found these results to be less reliable because of unusual climatic conditions (dry preceding years).

The change detection modelling methods suggested by Seibert & McDonnell (2010) were applied to assess wildfire effects on hydrology in the EEF. The objectives were:

1. to demonstrate the use of a simple model to assess disturbance-related changes in catchment runoff dynamics where a suitable control watershed is unavailable;
2. to quantify hydrologic changes by examining model residuals, model parameters and model simulations, with full consideration of parameter uncertainty; and
3. to interpret wildfire effects on hydrological processes at the catchment scale using the EEF dataset and the modelling approach.

The EEF runoff series were reconstructed for assumed unchanged conditions. In addition, model parameter sets calibrated for pre-fire conditions were compared to those for post-fire conditions both by comparing parameter values and by comparing simulations using the two groups of parameter sets.

STUDY SITE: THE ENTIAT EXPERIMENTAL FOREST

The EEF is located at 47°57′N, 120°28′W on the southwest-facing slope of the Entiat River valley on the eastern slope of the Cascade Mountains in central Washington State, US, about 55 km north of the city of Wenatchee. The EEF was originally established to study effects of road construction and timber harvesting on the quantity, quality and timing of streamflow. A detailed site description and review of the data are available in Helvey *et al.* (1976*b*) and Woodsmith *et al.* (2004); only a brief summary is given here.

Monitoring in the EEF started in 1960 and continued through 1977. McCrea, Burns and Fox Creeks drain adjacent catchments, which are each approximately 500 ha in size. Elevations range from 603 to 2164 m; mean aspects range from 205 to 237 degrees; mean channel gradients range from 27 to 29%; and the mean hillslope gradient is about 50%. At 920 m elevation, mean annual temperature is 6.7°C and mean annual precipitation is 580 mm. Most precipitation falls from November to May and only 10% occurs from June through September. Seventy percent of precipitation is snow, and hydrographs are dominated by snowmelt-driven peak flows in May or June (Helvey *et al.* 1976*b*). Annual runoff for the pre-fire conditions (1961–1969) varied between 112 and 175 mm for the three catchments (Helvey 1980).

Bedrock is predominantly granodiorite and quartz diorite. On the lower slopes, glaciofluvial sediment is common. Pumice deposits from multiple eruptions of Glacier Peak, which is 56 km to the northwest, vary from a few centimetres to more than 6 m in thickness. Soils are well-drained Entisols. The pre-fire forest overstory consisted predominantly of ponderosa pine (*Pinus ponderosa* Laws.) and, at higher elevations, Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco). Severe wildfires leading to stand replacing (i.e. complete destruction of large areas of forest) had apparently not occurred for 200 years prior to 1970, although fire scars on large trees indicated a history of less severe periodic fire (Helvey *et al.* 1976*b*).

Post-fire treatment differed among the EEF catchments. In Burns Creek and McCrea Creek roads were constructed and salvageable trees were harvested. These watersheds were also fertilized, seeded with grasses and planted with conifers. These treatments were not applied to Fox Creek in order to preserve it as a control for future study of treatment effects.

DATA COLLECTION

Precipitation was measured in shielded, weighing-bucket gauges having a 203 mm diameter orifice. Only one gauge in the study area (at the Burns Creek weir site) covers the entire period of record. In order to extrapolate this series to years before 1962 and to fill gaps in the precipitation record, data from three National Weather Service stations were used: Lake Wenatchee (#454446, 47°50′N, 120°48′W, 613 m above MSL), Stehekin 3 NW (#458059, 48°20′N, 120°42′W, 351 m above MSL) and Stevens Pass (# 458089, 47°45′N, 121°05′W, 1237 m above MSL). For these stations, which were located 25–50 km from the EEF, relationships with the precipitation measured by the Burns Creek gauge were determined and used to estimate precipitation for periods when data from Burns Creek were missing. Daily maximum and minimum air temperature measurements were available for the Burns weir site starting in 1966. Data from Stehekin 3 NW were similarly used to extend the EEF temperature record.

Discharge data were collected during the period 1960–1972 using sharp-crested, 120-degree, V-notch weirs near the mouth of each of the three experimental catchments. Stage height was measured using a stilling well float and punch tape recorder. On August 24 1970, the EEF catchments burned unexpectedly in a 486 km^2 wildfire caused by lightning (Helvey *et al.* 1976*a*; Martin *et al.* 1976). While Tiedemann *et al.* (1978) describe fire effects in the EEF as severe and uniform, a few small (generally less than 10 ha) patches of mature ponderosa pine survived the fire. One year after the fire, at the end of the 1971 growing season, native and seeded plants covered an average of only 8.6% of the land surface (Tiedemann & Klock 1973).

Debris flows were initiated in March 1972 by rapid melt of an unusually deep snowpack and again in June 1972 by intense rain storms. These debris flows destroyed the McCrea and Fox Creek weirs, which were quickly replaced with Parshall flumes. Nevertheless, post-fire gauging records for both McCrea Creek and Fox Creek were incomplete due to persistent post-fire sedimentation in the flumes. The one surviving weir at Burns Creek provided the most complete post-fire discharge dataset, and missing data for 1973–1975 for the other two catchments were estimated from discharge at the Burns Creek weir (Helvey 1980; Helvey & Fowler 1999).

MODEL AND APPROACH

The HBV model

The conceptual HBV model (Bergström 1976, 1992) simulates daily discharge using daily rainfall and temperature and monthly estimates of potential evaporation as input. The model consists of a set of routines with 12 model parameters describing snow, soil moisture, groundwater and routing processes (Figure 1(a)). Snow accumulation and melt is computed using a threshold temperature (TT) and a degree-day coefficient (CFMAX). Whenever precipitation is simulated as snow (temperature is below TT), then the amount of precipitation is multiplied by a snowfall correction factor (SCF). This parameter partly compensates for systematic measurement errors related to snowfall, but its primary purpose is to compensate for snow evaporation mainly from intercepted snow, a water loss that is not otherwise included in the model. Usually SCF is smaller for forested than for open areas (Seibert 1999).

Actual evaporation and groundwater recharge from rainfall and snowmelt are computed in the soil routine as functions of actual water storage and maximum soil moisture storage capacity (FC) in the soil model box. There is no separate vegetation or interception routine in the HBV model; rather FC includes vegetation effects implicitly in the soil routine. Higher values of FC reflect greater soil water storage capacity and thus greater water availability for evaporation. Runoff from the groundwater model boxes is calculated using three linear reservoir equations and channel routing is simulated by a triangular weighting function. Calculations are performed for each elevation zone for both the snow and the soil routines, whereas the lower box of the response routine is a lumped representation of the catchment. The model is described in detail elsewhere (Bergström 1992; Lindström *et al.* 1997; Seibert 1997). The version of the model used in this study, 'HBV Light', generally corresponds to the original version (Bergström 1992, 1995). The agreement between observed (Q_{obs}) and simulated (Q_{sim}) catchment runoff was evaluated by the model efficiency (Nash & Sutcliffe 1970), here called R_{eff}:

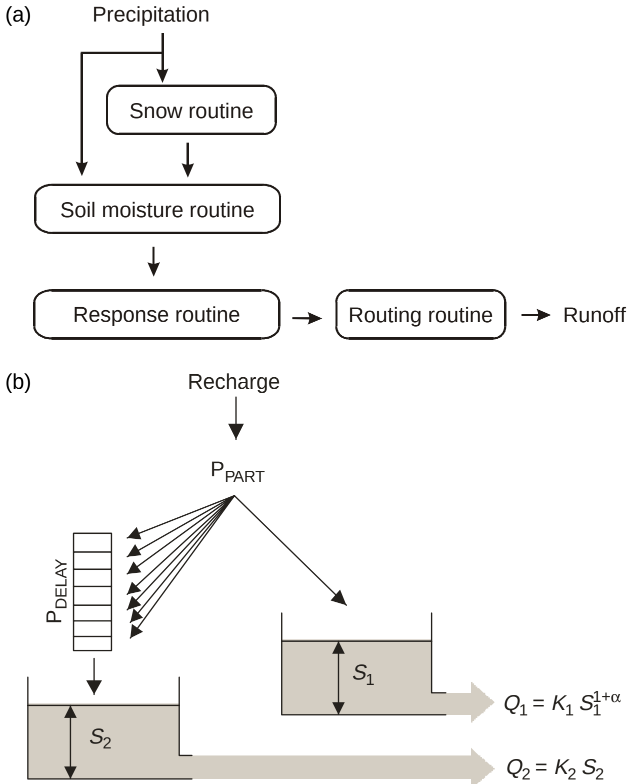

Figure 1 | The HBV model: (a) general model structure and (b) response routine, modified compared to the traditional response function for application in the Entiat experimental forest. See text for further explanation.

$$R_{\mathrm{eff}} = 1 - \frac{\sum (Q_{\mathrm{obs}} - Q_{\mathrm{sim}})^2}{\sum (Q_{\mathrm{obs}} - \overline{Q_{\mathrm{obs}}})^2} \tag{1}$$

Initial model runs indicated that the traditional HBV model structure did not adequately predict the contribution of groundwater to runoff in the EEF catchments. An alternative groundwater response function (Bergström & Sandberg 1983; Seibert 2000) was therefore implemented in which the simulated recharge from the soil routine is divided into two parts (Figure 1(b)): (1) A certain portion of the recharge, P_{PART}, is added directly to a nonlinear storage box. Runoff from this box is computed as $Q_1 = K_1 S_1^{1+\alpha}$. (2) The remaining recharge is evenly distributed over a subsequent period of P_{DELAY} days to a linear storage box ($Q_2 = K_2 S_2$). The latter storage represents deep groundwater where recharge is delayed (Figure 1(b)) and is consistent with runoff processes observed at the site (Alley 2007). This indication of the importance of deep groundwater is noteworthy, and was not quantified by previous authors. The sum of Q_1 and Q_2 is, after routing by a triangular weighting function, identical to the simulated catchment runoff determined by the usual HBV model.

Model application

The HBV model was applied to the three study catchments using daily precipitation and temperature series as well as long-term mean monthly potential evaporation. Potential evaporation was estimated based on Class A evaporation pan measurements at the Western Regional Climate Center (WRCC), Wenatchee Experiment Station for 1950–1997 (WRCC 2003). The catchments were divided into four elevation zones, and a temperature lapse rate (-0.6°C per 100 m) was applied. Measurements of precipitation at different elevations during short periods indicated that there was no clear change in precipitation amounts with elevation and, thus, no lapse rate for precipitation was used. Series were divided into pre- (1961–1966) and post-fire (1970–1976) water years. In all cases at least one year was used as a model 'warm-up' period. These periods were consistent with the general recommendation that 5–10 years of data are needed to calibrate models such as the HBV model (Bergström & Sandberg 1983; Seibert 2000). This allowed for adequate constraint of the model parameterization, while retaining sufficient resolution to detect changes caused by the wildfire.

Model parameters are highly interdependent, and different parameter sets can be in agreement for one period but not another (Beven 2001). To address this problem of parameter uncertainty, a Monte Carlo technique was employed which allowed for computation of parameter ranges and confidence intervals. For each catchment, the model was run using 1,000,000 parameter sets randomly chosen within feasible ranges, and the model efficiency (R_{eff}) was computed for both the pre- and post-fire period. By this means, the 100 best (i.e. highest efficiency) parameter sets for each period were determined. Only these 100 sets were used in further analyses. This number limits analyses to the most efficient parameter sets, while capturing the variability among them. Tests indicated that results did not vary significantly when twice or half as many parameter sets were used.

For each catchment a series of peak runoff events was selected from the data. To be included a peak had to be at least twice as large as the long-term mean. Only the highest peak within any 10-day period was included to avoid counting multiple peaks from the same event. Events were classified by season as either spring or fall events.

Change detection

Three approaches to detect runoff changes were used: evaluating model residuals, comparing parameter values and comparing simulations using different parameter sets (Figure 2).

Model residuals

Runoff series were reconstructed on the basis of unchanged conditions, and these simulations were compared to observed values (Figure 2(a)). Model residuals (d_i) were computed as differences between observed (Q_{obs}) and simulated (Q_{sim}) peak flows (Equation (2)), and model residuals for each flow event (i) using each parameter set were evaluated (Figure 2(a)).

$$d_i = Q_{\mathrm{obs},i} - Q_{\mathrm{sim},i} \tag{2}$$

Residuals should scatter around zero for events during a reference period and periods without any change in precipitation–runoff relationships caused by land-use change, fire or other disturbance. Post-disturbance residuals larger than zero indicate increased runoff (Figure 2(a)).

Parameter values

Parameter values differ whenever a model is calibrated for different periods that include significant land-cover or land-use change. Parameter value differences can be used to evaluate changes in the hydrological behaviour

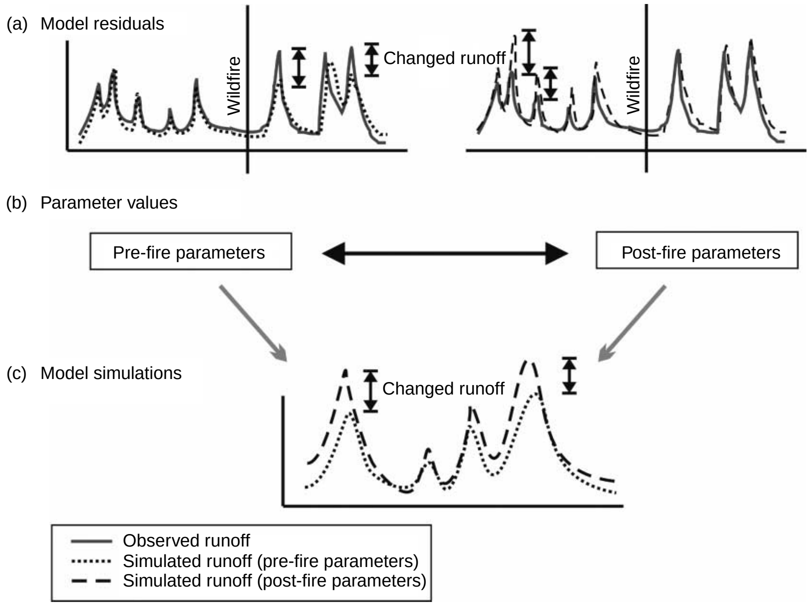

Figure 2 | Schematic overview of the three different modelling approaches to evaluate impacts of land-use or land-cover changes on catchment hydrology.

integrated at the catchment scale. The analysis of change in parameter values is, however, not straightforward. One problem is parameter uncertainty which means that various combinations of parameter values might be equally likely for the same period. Considering single parameter values, one might observe differences between periods even if there is actually no change at all. To tackle the problem of parameter uncertainty distributions of parameter values were compared, rather than single values, of the best pre- and post-fire parameter sets (Figure 2(b)).

Simulations using different parameter sets

Since various parameters are interrelated in the HBV model, as in most models, it might be difficult to fully evaluate change by only looking at individual parameters. An alternative approach to testing for change in hydrologic behaviour is to assess whole parameter sets rather than individual parameters. Here the different parameter sets are assumed to capture the system behaviour for pre- and post-fire conditions. The magnitude of runoff peaks simulated from the 100 most efficient pre- and post-fire parameter sets was compared, using climatic data for all observed events to drive these scenarios (Figure 2(c)). Simulations were summarized for the two periods by calculating median peak flows over all simulations for each event. Relative differences (D_i) in peak flows were calculated using Equation (3), where Q_{pre} and Q_{post} are the peak flows simulated with parameter sets for pre- and post-fire periods, respectively:

$$D_i = \frac{Q_{\mathrm{pre},i} - Q_{\mathrm{post},i}}{(Q_{\mathrm{pre},i} + Q_{\mathrm{post},i})/2} \tag{3}$$

RESULTS

Model efficiencies ranging from 0.72 to 0.79 and from 0.68 to 0.71 for pre-fire and post-fire periods, respectively, were obtained for the three experimental catchments through calibration with the modified HBV model for both pre- and post-fire conditions (Table 1). For pre-fire parameter sets model residuals clearly increased after the fire (Figures 3 and 4). In other words, observed post-fire

Table 1 | Model efficiencies (Nash & Sutcliffe 1970) for the pre-fire and post-fire period for the different catchments

Catchment	Best fit for pre-fire period	Best fit for post-fire period
Burns	0.75	0.71
Fox	0.79	0.68
McCrea	0.72	0.68

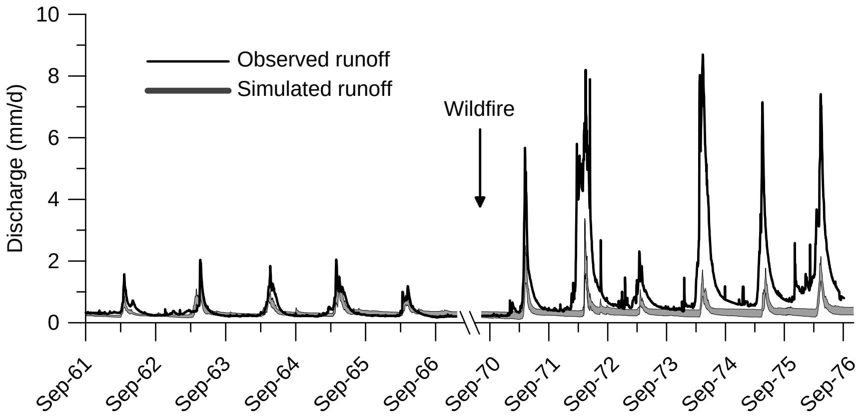

Figure 3 | Observed runoff (black line) and runoff simulations using pre-fire parameter values (Burns Creek). For the simulated runoff the range (10th to 90th percentile) of simulations is shown by the grey area.

peak flows were higher than those predicted by the model based on pre-fire parameters (i.e. those which would have been observed if a fire had not occurred). The effect was most obvious for the spring snowmelt events. Over the three experimental catchments, peak flows increased by 120% post-fire on average.

Values of several model parameters differed between pre- and post-fire periods. The snow routine parameters were particularly affected. For the threshold temperature above which snowmelt starts (TT), lower values were found for the post-fire period (Figure 5(a)). Average TT values over the three catchments were 3° lower after the fire (Table 2, Figure 6(a)). Values for the snowfall correction factor (SCF) increased, indicating increased snow accumulation post-fire (Figure 5(b)). SCF was, on average over three catchments, less than 1 before the fire and increased by about 50% after the fire (Table 2, Figure 6(b)). Also, the degree-day factor (CFMAX) increased for all catchments indicating more rapid post-fire snowmelt (Table 2).

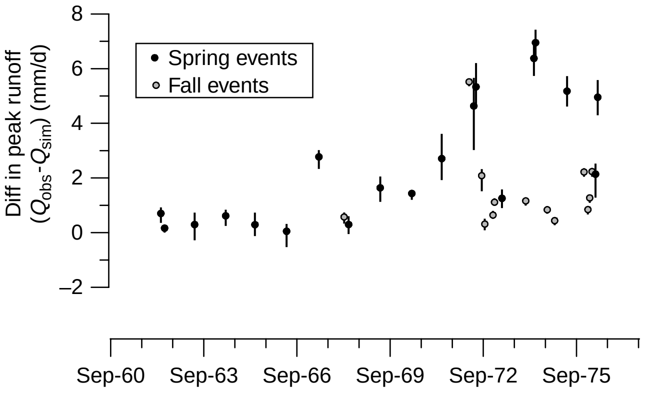

Figure 4 | Change detection through comparison of model residuals for simulations using pre-fire parameter values (Burns Creek), median values (circles) and range of 10th and 90th percentile (vertical line).

In the soil routine, fire mainly affected the soil water storage capacity parameter FC (Figure 5(c)). For the Entiat catchments about 50% smaller values for FC were found after the fire (Table 2, Figure 6(c)). The parameter C_{PART} increased which means that the portion of recharge contributing to runoff through the non-delayed response box increased. On the other hand, the recession coefficient for the flow from this box (K_1) decreased (Table 2). The combined effect on runoff of all changes in individual parameter values was evaluated by using the 100 best pre- and post-fire parameter sets to simulate all storm events for the Entiat catchments. For each event the medians of the simulations using pre-fire and those using post-fire parameter sets were computed. For all three catchments, simulated peak flows were about 150–200% higher when using the post-fire parameter sets compared to the simulations using the pre-fire conditions (Figure 7). For the spring events the difference (separation from the 1:1 line in Figure 7) was greater for the larger events.

DISCUSSION

Change detection modelling of runoff

Quantifying the catchment scale effects of natural wildfire on runoff response is difficult. Here, the change detection modelling approach has been used as a tool for assessing

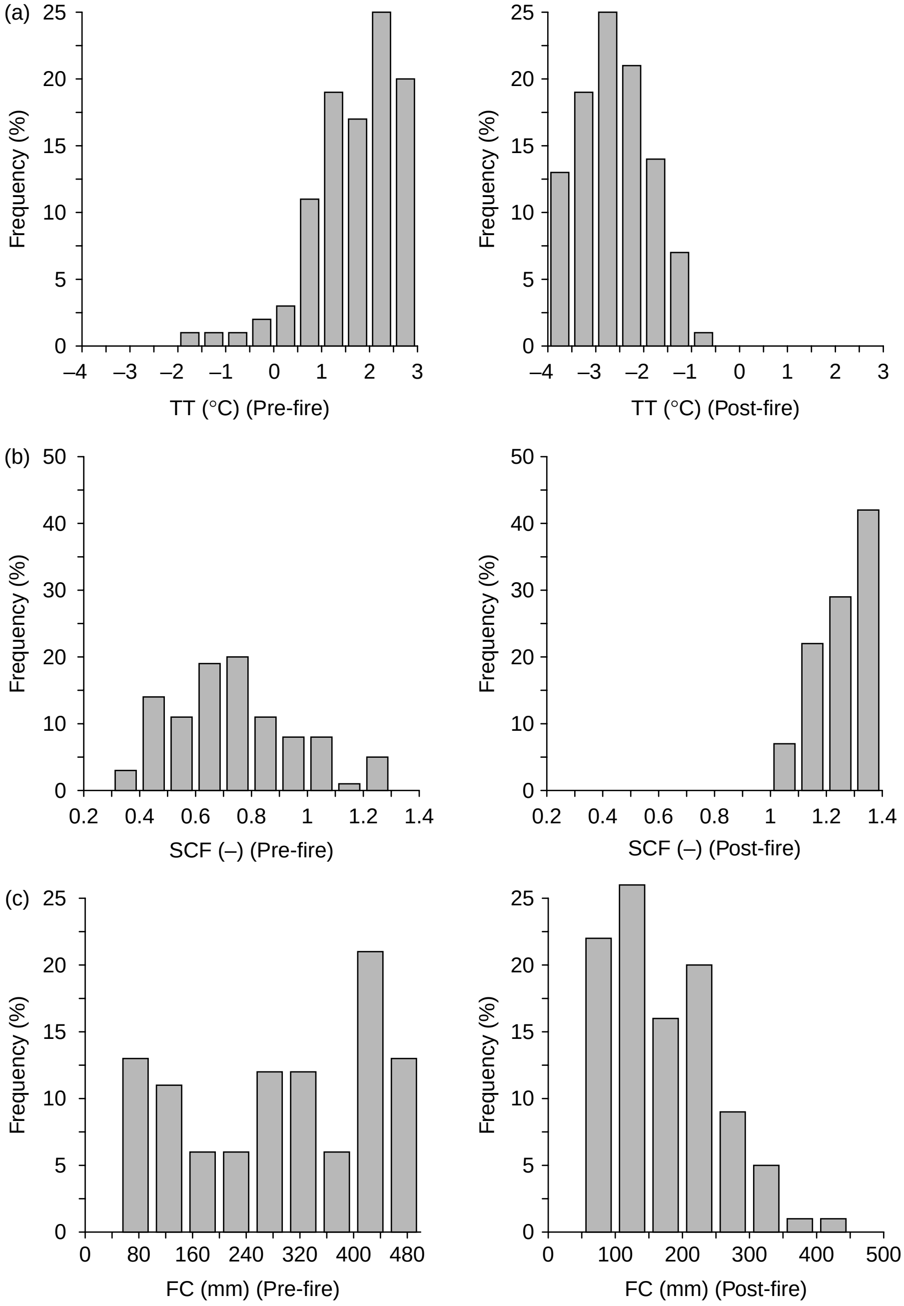

Figure 5 | Distributions of parameter values for pre- and post fire conditions for Burns Creek: (a) threshold temperature (TT); (b) snowfall correction factor (SCF) and (c) soil storage capacity (FC).

fire effects on flow. The application of the HBV model as a change detection tool indicated increases in peak flows following severe wildfire and related road building and harvesting of dead and damaged forest vegetation. These results are qualitatively similar to those of Helvey (1980) who found that, during the post-fire water years (1972–1977), measured runoff in Burns Creek exceeded predictions by 100–500 mm. However, Helvey's paired-watershed analysis was limited to a comparison of annual water yields, because the control was a considerable distance from the study watershed and much larger in size. In contrast, the modelling approach used in this study

Table 2 | Medians of parameter value distributions for pre- and post fire conditions. Significant differences are marked by + (increase) or − (decrease) ($p < 0.001$, Wilcoxon rank-sum test)

			Burns			Fox			McCrea		
Parameter	**Meaning**	**Units**	**Pre-fire**	**Post-fire**	**Change**	**Pre-fire**	**Post-fire**	**Change**	**Pre-fire**	**Post-fire**	**Change**
TT	Threshold temp.	°C	1.9	−2.7	−	2.2	0.1	−	2.4	−0.9	−
CFMAX	Degree-day factor	mm $°C^{-1}$ d^{-1}	2.8	3.5		1.8	4.0	+	2.1	3.8	+
SCF	Snowfall correction	–	0.71	1.28	+	0.86	1.19	+	0.70	1.17	+
FC	Max. soil moisture (SM)	mm	304	151	−	298	109	−	356	167	−
LP	Evaporation reduction threshold (SM/FC)	–	0.67	0.65		0.67	0.53		0.75	0.57	
BETA	Shape coefficient	–	1.55	3.23	+	2.06	3.68	+	1.57	2.63	+
C_{PART}	Portion non-delayed recharge	d^{-1}	0.236	0.471	+	0.303	0.485	+	0.346	0.397	+
C_{DELAY}	Delay of recharge to the delayed box	d	44	27		30	38		43	49	
α	Non-linearity coefficient (delayed response)	–	0.23	0.14		0.23	0.17		0.29	0.15	
K_1	Recession coefficient (non-delayed response)	d^{-1}	0.059	0.029	−	0.031	0.022	−	0.065	0.032	−
K_2	Recession coefficient (delayed response)	d^{-1}	0.0004	0.0053	+	0.0026	0.0038		0.0021	0.0010	−
MAXBAS	Length of weighting function (routing)	d	2.45	2.46		2.36	2.34		2.78	2.36	

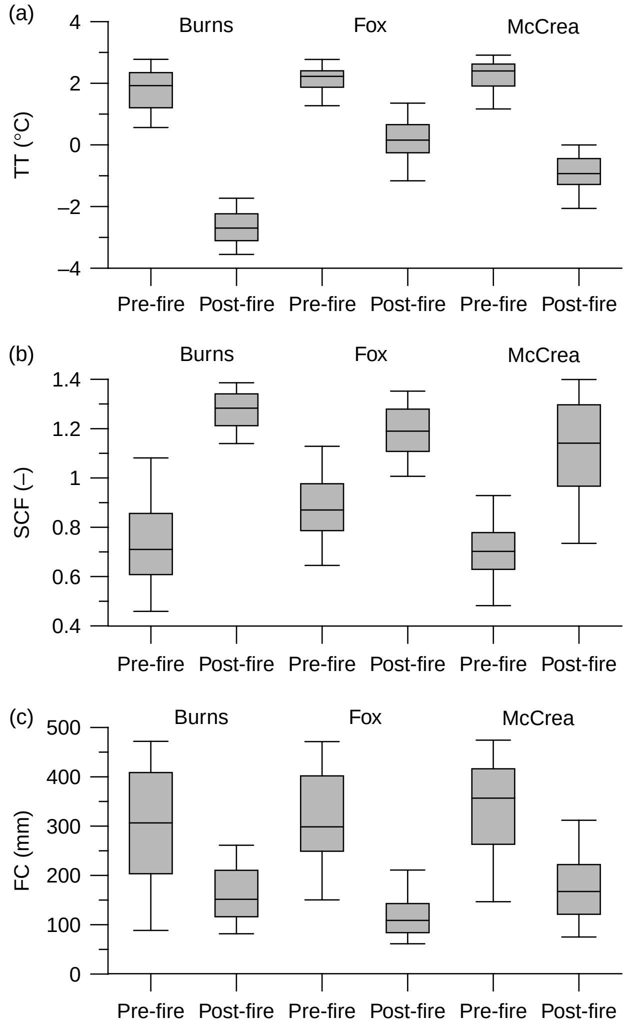

Figure 6 | Box plots of the distributions for parameter values for pre- and post fire conditions for the three catchments: (a) TT; (b) SCF; and (c) FC (the box plots indicate median as well as the 10th, 20th, 80th and 90th percentiles).

allows us to discuss processes forcing change in hydrological behaviour in more detail and to quantify the increase in daily peak flow rates.

Post-fire treatment differed among the EEF catchments. From the change response that could be quantified in this study, however, no significant differences in responses among the watersheds could be seen. This suggests that fire effects overwhelmed differences in management treatment effects in the first years after the fire.

Change detection model as a process learning tool

The analyses presented here reveal an advantage of change detection modelling over the paired-watershed approach,

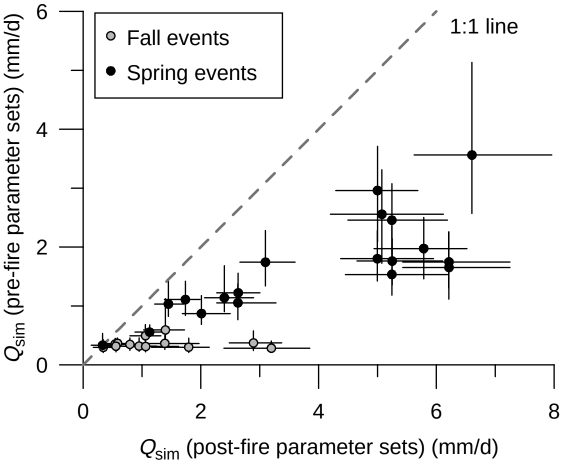

Figure 7 | Median and range of peak runoff calculated with the pre- and post-fire parameter sets for Burns Creek (lines span the 10th to 90th percentile range).

in that quantifying change in model parameters facilitates identification and interpretation of the processes responsible for measured hydrologic change. Parameter changes suggest that reduced forest canopy cover contributes to increased peak flows by increasing snow accumulation on the ground and increasing snowpack exposure to energy sources. A post-fire increase of approximately 50% in the snow fall correction factor (SCF) indicates increased snow accumulation (greater water equivalent in the snow pack) due to reduced evaporative loss. The decrease of the threshold temperature parameter (TT) following fire indicates initiation of melt at a lower temperature. For average temperature conditions during spring, the change of TT implies that seasonal snowmelt would begin about one month earlier. This change likely reflects increased incoming solar radiation and turbulent energy exchange at the snow surface following removal of the forest canopy. The increased exposure of the snowpack also relates to a post-fire increase of about 50% in the degree-day parameter associated with snowmelt rate (CFMAX), suggesting a more rapid melt.

A post-fire decrease of approximately 50% in the parameter associated with soil moisture storage capacity (FC) suggests that less storage is available. This change implies a post-fire increase in routed storm runoff, either as rapid flow to the channel system or through groundwater recharge. As discussed above, interception is implicitly included in the soil routine and the decreased values for FC are also a result of reduced interception following the fire. Water repellence of the soils after the fire might be another explanation for the increased runoff. The parameter changes in the response routine were more difficult to interpret. While a larger portion of recharge contributed to the non-delayed response box, the recession coefficient for flow from this box decreased after the wildfire. This finding illustrates that although changes in individual model parameters can inform process understanding, parameter interaction can obscure direct relationships. Therefore, changes of parameter sets rather than the change of single parameters should also be compared. Comparing simulated runoff using different parameter sets allowed evaluation of the combined effect of parameter value changes on runoff simulations. This is assumed to be often of more interest than the change of certain parameter values.

New directions for fire-water research by change detection modelling

The variation in parameter values within the best sets for pre- and post-fire conditions reflects parameter uncertainty in the model. The HBV model used in this study had 12 parameters. While this is a small number compared to many other models, these are still more parameters than can be fully identified from the information contained in the precipitation–runoff series. This parameter uncertainty, or equifinality of different parameter sets, is commonly recognized in hydrologic modelling (e.g. Pappenberger & Beven 2006), but is an issue rarely addressed in modelling approaches to detect changes (Seibert & McDonnell 2010). Using a large number of parameter sets rather than a single set of parameter values facilitates assessment of this uncertainty. Using these collections of sets provides distriutions of simulations or parameter values rather than single values in each of the three approaches used to analyze changes. These distributions can be displayed graphically as distributions or as ranges to facilitate interpretation (Figures 3–7).

The considerable parameter uncertainty also indicated that it would have been very difficult to determine reasonably precise parameter values for a more complex model with more parameters. Model complexity has to be limited in order to be able to determine parameter values (within uncertainty ranges) and interpret parameter-value changes. Using a more physically based model with parameters, which at least in theory could be measured in the field, would not help in the change detection approach used in this study. This is because the calibration process is needed to evaluate parameter interactions associated with observed changes in hydrological catchment behaviour.

The HBV model was chosen in this study as it provides a compromise between black box models, which do not provide a basis to discuss (internal) catchment processes, and complex models, for which parameters could not be identified at all. While the agreement of observations and HBV model simulations was not perfect, the model performance was assumed to be acceptable for the change detection purposes in this study. Based on tests with various model structures, it seems that the reason for not achieving better fits between simulations and observations was data quality rather than the choice of the model.

CONCLUDING REMARKS

Three different approaches were utilized for change detection modelling employing a modified version of the HBV model to conclude that catchment-scale runoff increases following severe wildfire. Model residuals from simulations based on pre-fire parameters indicate an average peak flow increase of 120%. Comparable results are obtained from simulations using different calibrated model parameter sets for pre- and post-fire conditions. The results suggest that these are reasonable alternative approaches to more traditional paired-watershed techniques of quantifying change in catchment hydrology.

An important benefit of this modelling approach is that, in addition to quantification of change resulting from a disturbance, comparison of model parameters between pre- and post-fire periods provides an indication of how hydrological processes may be altered by severe fire. Post-fire changes in parameter values suggest process-based explanations for the observed peak flow increases. Given the uncertainties of and interactions between the different model parameters, such explanations need to be approached with caution. Nevertheless, these suggestions of altered processes can direct further investigation and hypothesis formulation. The findings of change in model parameters caused by the wildfire will help to predict effects of land-cover changes in other catchments in future studies. In addition, modifications of the model structure such as the use of an alternative response routine to represent deep groundwater recharge, may also allow for future hypothesis testing.

ACKNOWLEDGEMENTS

The authors thank the three anonymous reviewers for their valuable comments which helped to clarify the text.

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First received 20 March 2009; accepted in revised form 30 October 2009. Available online June 2010