The Entiat Experimental Forest: A Unique Opportunity to Examine Hydrologic Response to Wildfire

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Water is generally regarded as the most important natural resource in the interior Columbia River basin (ICRB). Public agencies managing forested headwater source areas are under increasing pressure to document water quantity and quality, and the effects of background and anthropogenic disturbances that influence them. Fire is widely recognized as the primary disturbance process affecting ecological systems in the ICRB. For these reasons land management agencies seek a more complete understanding of processes that generate and maintain streamflow as well as effects of fire and post-fire treatments on water quantity and quality. Although effects of wildfire are issues of major concern, they remain poorly understood at the catchment scale, largely because site specific data from both before and after wildfire are rare. The Entiat Experimental Forest (EEF) in central Washington State provides this type of hydrologic record of fire effects, owing to a severe wildfire during the summer of 1970, following ten years of stream gaging as part of a controlled land use experiment. Data collection continued after the fire through 1977. The entire dataset provides an archive for assessment of hydrologic response and model formulation, calibration, and testing. Research at the EEF is being revived to model effects of fire on water quantity and quality, including effects on water source, flowpath, timing, and post-fire recovery of hydrologic processes. We are taking a diagnostic approach to gaging to understand internal catchment behavior and develop a functional characterization of the EEF catchments. Change detection modeling employing the Hydrologiska Byråns Vattenbalansavdelning [HBV] rainfall-runoff model is being applied by: (1) comparing observed runoff to runoff simulated from pre-fire parameters, (2) comparing simulations based on pre-fire parameters to simulations based on post-fire parameters, and (3) directly contrasting pre-fire with post-fire parameter values. Preliminary modeling results suggest that effects of the 1970 fire included greater snow accumulation, earlier initiation of snowmelt runoff at lower mean air temperatures, more rapid melt, increased soil moisture, and sharply increased runoff. Gaging at other catchments in the larger Entiat River subbasin creates a foundation for nested watershed monitoring and modeling to address spatially distributed hydrologic processes in this portion of the ICRB.

Keywords: *hillslope hydrology, conceptual catchment modeling, rainfall-runoff modeling, HBV runoff simulation model, fire effects*

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Introduction

Water is generally regarded as the most important natural resource in the interior Columbia River basin (ICRB). It is essential for human consumption, ecosystem function, and habitat for aquatic organisms, including sensitive species. Water supports a multi-billion dollar economy in agriculture, power generation, recreation, mining, and manufacturing. Public agencies managing forested headwater source areas are under increasing pressure to document effects of background and anthropogenic disturbances on water quantity and quality.

Fire is widely recognized as the primary disturbance process affecting ecological systems in the ICRB. Fire can affect snow accumulation, snowmelt, surface runoff, subsurface water routing and storage, timing and quantity of streamflow, chemical and thermal water quality, aquatic habitat of sensitive species, and human water use. For these reasons land management agencies seek a more complete understanding of processes that generate and maintain streamflow, and of the effects of disturbance, such as fire and post-fire treatments, on water quantity and quality.

Major wildfires are bringing increasing attention to potential effects of fire and associated land management activity, such as fire suppression and salvage logging, on water quantity and quality. This is particularly true in the western U.S. and some European countries where large, severe wildfires are perceived to be occurring with greater frequency (Conedera et al. 2003; Pierson et al. 2001; Rieman et al. 2003; Robichaud and Elsenbeer 2001). Similarly, effects of post-fire rehabilitation on runoff, peak flows, erosion, sedimentation, and other fire-affected processes is receiving increasing attention (Robichaud et al. 2000).

Fire has been an important disturbance process in the ICRB for millennia (Hessburg and Agee 2003; Wright and Agee 2004). Damage to forest vegetation and the litter layer by fire can expose soil to rainsplash and hasten delivery of precipitation to the soil surface, thereby increasing runoff and surface erosion (Johansen et al. 2001; Robichaud and Brown 1999). Soil infiltration capacity can be reduced when surface pores are sealed by ash or fine sediment made available by destruction of soil structure and mobilized by rainsplash, and by fire-induced formation of hydrophobic (water repellant) compounds on the soil surface (DeBano et al. 1977; DeBano et al. 1998; Giovannini et al. 1988; Martin and Moody 2001; Robichaud and Hungerford 2000; Wells 1981; Wright and Bailey 1982). Reduced infiltration through these mechanisms and reduced evapotranspiration caused by damage to vegetation can result in increased runoff, flooding, sediment mobilization and delivery to channels, and debris flows (Beschta 1990; Cannon et al. 2001; Conedera et al. 2003; Elliott and Parker 2001; Krammes and Rice 1963; Meyer and Wells 1997; Tiedemann et al. 1979; Wells1987). Increased peak flows can increase channel bed and bank erosion, further increasing sediment concentration in streamflow (Beschta 1990; Swanson 1981; Wondzell and King 2003). Large volumes of soil and nutrients can be transported to channels by fire-related debris flows (Helvey et al. 1985; Meyer et al. 2001).

Fire can also affect water quality by increasing nutrient losses to erosion, reducing nutrient uptake, and increasing leaching (Beschta 1990; Richter et al. 1982). Fire can volatilize nitrogen in vegetation and litter, increase nitrification, and mineralize cations, which may be redistributed and converted to more soluble salts. Increased runoff can result in increased total cation and bicarbonate losses (Grier 1975; Tiedemann et al. 1979; Wells et al. 1979). Fire can also increase stream water temperature, primarily by increasing exposure to solar radiation (Anderson et al. 1976, Beschta 1990; Tiedemann et al. 1979). Recovery of pre-fire watershed conditions depends largely on recovery of terrestrial plant communities, with associated increases in infiltration and evapotranspiration (Pierson et al. 2001; Swanson 1981; Wright and Bailey 1982).

Despite the importance of wildfire as an ecological and social issue, relatively few hydrologic data exist beyond the plot and hillslope scales. Fire data at the catchment scale are mostly associated with paired watershed studies of prescribed fire effects on water quantity and quality. Catchment scale hydrologic effects of wildfire are less well known, because pre-fire data are rarely available (Moody and Martin 2001). Previously published work having site-specific, pre-wildfire data includes a study from the San Dimas Experimental Forest in southern California (Hoyt and Troxell 1934) and one from a eucalyptus forest in Australia (Langford 1976).

Another of these rare "natural fire experiments" comes from the Entiat Experimental Forest (EEF), located in central Washington State (Helvey 1980). Data from the EEF provide a resource for model formulation, calibration, and testing of wildfire effects on catchment scale runoff. These data also provide an opportunity to contrast long-term hydrologic recovery between catchments that were or were not subject to post-fire rehabilitation treatments (Woodsmith et al. 2004). In this paper we focus on effects of fire on runoff. We present background information on the EEF and historical data collection. We then discuss our objectives and approach to current and future investigations, and the preliminary results of hydrologic change detection modeling.

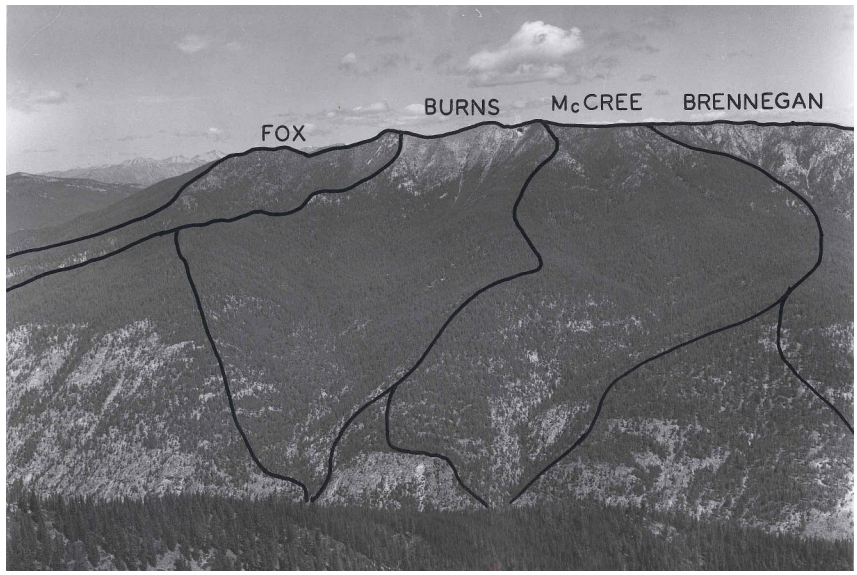


Figure 1. The Entiat Experimental Forest, looking toward the northeast.

The Entiat Experimental Forest

The EEF consists of three adjacent catchments, McCree Creek, Burns Creek, and Fox Creek, each approximately 500 ha in size (Figure 1). They are subwatersheds in the Entiat River subbasin in central Washington State on the east slope of the Cascade Range about 55 km north of Wenatchee at latitude 47°57'N, longitude 120°28'W. Catchment elevations range from 549 to 2134 m, mean aspects from 205 to 237 degrees, mean channel gradients from 27 to 29 percent, and mean hillslope gradient is about 50 percent. Mean annual temperature at 920 m elevation is 6.7°C. Mean annual precipitation is 58 cm; most falls from November to May, and only 10% falls from June to September. Seventy percent of precipitation is snow, and hydrographs are dominated by snowmelt. Annual peak flows occur in May or June. During the period 1962-1970, fifty percent of the time discharge was greater than 12.7, 20.7, and 19.2 liters per second (L/s) and mean maximum daily flow was 164.4, 243.7, and 167.2 L/s in McCree, Burns, and Fox Creeks respectively (Helvey 1974; Helvey et al. 1976a; Tiedemann et al. 1978).

Bedrock is primarily granodiorite and quartz diorite. Glaciofluvial sediment is abundant on the lower slopes. Glacier Peak is 56 km to the northwest, and pumice deposits from multiple eruptions vary from a few centimeters to more than six meters in thickness. Soils are well-drained Entisols. Prior to a severe fire in 1970 the forest overstory consisted predominantly of ponderosa pine (*Pinus ponderosa* Laws.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) at higher elevations. Stand-replacing wildfire had apparently not occurred in the 200 years prior to 1960, although fire scars on large trees indicated a history of periodic fire (Helvey et al. 1976a).

Studies on the EEF were originally established to examine effects of timber harvesting and road building on quantity, quality, and timing of streamflow. Site selection criteria included: (1) three or more 2.5-15.5 km2 catchments; (2) similarity among catchments in climate, physical characteristics, and vegetation, all of which should represent much of the forested land east of the Cascade Range crest in Washington State; (3) absence of disturbance by recent fire, heavy grazing, logging, or road building; and (4) reasonable year-round access (Helvey et al. 1976a).

Historical Data

Data collection in the EEF began in 1960 and continued through 1977. During the period 1960-1970 discharge data were collected using sharp-crested, 120-degree, V-notch weirs near the mouth of each of the three experimental catchments. Weir ponds had capacities of 20-50 m^3. Stage height was measured using a stilling well float and punch tape recorder.

Following 10 years of calibration, the EEF catchments burned unexpectedly on 24 August 1970 as part of a 486 km^2, lightning-caused wildfire complex (Helvey 1980; Martin et al. 1976). Tiedemann et al. (1978) describe fire effects in the EEF as severe and uniform. However a few small patches, generally less than 10 ha, of mature ponderosa pine survived. By the end of the 1971 growing season, land surface cover by native and seeded plants averaged only 8.6 percent (Tiedemann and Klock 1973). During the fire, discharge in McCree Creek declined from 6.25 to 1.71 L/s, and immediately after the fire, strong diurnal discharge patterns were nearly eliminated owing to reduced transpiration (Berndt 1971).

After the fire two contour roads were constructed in McCree and Burns catchments, dead trees were logged, and

grass and clover seed and nitrogen fertilizer were applied by helicopter (Helvey 1980). Fox Creek was designated an experimental control and not seeded, fertilized, roaded, or logged (Tiedemann and Klock 1976). Effects of wildfire on streamflow quantity, quality, and timing became primary research objectives, and were examined until the cessation of data recording in 1977 (Helvey 1980).

In mid-March 1972 record high air temperatures and an exceptionally deep snowpack produced flows greater than three times the maximum measured during calibration in McCree Creek. On 18 March a debris flow, apparently initiated by failure of weathered granitic material on steep slopes, destroyed the McCree Creek weir. Intense rainstorms on 9 and 10 June initiated a similar failure and debris flow in Fox Creek, destroying that weir (Helvey 1974). These weirs were replaced during the summer and autumn of 1972 with Parshall flumes at the gauging sites. Post-fire gaging records for McCree and Fox Creeks were incomplete owing to persistent sedimentation in the flumes. During 1973-1975 those missing data were estimated from discharge at the Burns weir (Helvey 1980; Helvey and Fowler 1999). Record quality, based on U.S. Geological Survey standards (Corbett 1943), was excellent for all stations until 1972. Records for Burns were good for 1972-1977 and fair to poor for Fox and McCree (Helvey and Fowler 1999). During the first post-fire year total water yield from the EEF was 50% greater than predicted using the Entiat River and nearby Chelan River as controls (Helvey 1974). The most complete post-fire discharge data were from Burns Creek. During water years 1972-1977 measured runoff in Burns Creek exceeded predictions by 10.7 to 47.2 cm, using the Chelan River as a control (Helvey 1974).

Precipitation was measured in shielded weighing-bucket gages with a 203-mm orifice. Only one gage in the study area, approximately 200 m from the Burns Creek weir, covered the entire period of record. After 1972 storage gages were installed at nine locations distributed throughout the McCree and Burns catchments. High elevation gages were serviced only once each year due to difficult access, but a more frequent schedule was kept where feasible. These other gages provided data for periods of approximately one year each. An additional six gages within 48 km of the EEF have records covering the study period (Bowles et al. 1975).

Water temperature sensors and punch tape recorders were installed in 1968 at the three gaging stations and temperature was recorded hourly. Three additional recorders were installed in Fox Creek in the fall of 1972 (Helvey and Fowler 1999). Mean daily maximum water temperatures during December 1969 to February 1970 were approximately 3°C, and 10 to 11°C in July and August before the 1970 fire (Helvey 1974; Helvey et al. 1976b). During the first two post-fire years mean daily maximum water temperatures increased in Burns Creek by 5-6°C based on control data from the Entiat River (Helvey 1974; Helvey et al. 1976b). In general stream temperatures peaked in the summer 1973 and declined until the end of data collection in 1977 (Helvey and Fowler 1999).

Beginning in 1966 air temperature and humidity measurements were made using a hygrothermograph and chart recorder at the Burns weir weather station. Daily maximum and minimum values were recorded (Helvey and Fowler 1999). Mean daily maximum air temperatures during December 1969 to February 1970 were -1.1°C, and 32.2°C in July and August before the 1970 fire (Helvey 1974; Helvey et al. 1976b). Tests for post-fire changes in mean monthly air temperature were inconclusive (Helvey et al. 1976b). Aerial measurements of midslope soil and plant surface temperatures were made on 29 August, 1969, near the time of maximum daily air temperature. Mean values ranged from 19.8 to 22.9°C (Tiedemann et al. 1978). Post-fire vegetation development for the years 1971-1974 is summarized in Tiedemann and Klock (1976).

Current and Future Investigations

The EEF provides a rare opportunity to investigate hydrologic recovery from severe wildfire, post-fire salvage logging, and rehabilitation treatments by drawing from its rich data record and initiating new studies of fire effects on water quantity, quality, and temperature (Woodsmith et al. 2004). In 2003 we began reanalyzing the EEF historical records and reinstrumenting the three gaging stations with redundant stage height recorders (pressure transducers and capacitance rods) and water temperature sensors. We reinstrumented the former Burns weir (920 m) and Fox Creek (650 m) weather stations with rain, air temperature, humidity, barometric pressure, and wind speed sensors, all recording to data loggers. During spring 2004 two similar weather stations were added, one on the eastern McCree catchment divide (1300 m) and one on the Burns-Fox divide (2000 m) (Figure 1). In addition, Parshall flumes with recording pressure transducers were installed on Burns Creek and on one of its tributaries at about 1200 m elevation, and 30 self-contained, logging water temperature sensors were installed along the entire length of Burns Creek.

Objectives of current and future research include: (1) reanalysis of historical data to assess fire effects on runoff; our results will be compared to those previously published for the EEF using traditional paired watershed approaches; (2) contrasting hydrologic recovery between

catchments where post-fire rehabilitation measures were applied (McCree and Burns) vs. no treatment (Fox); (3) assessment of post-fire hydrologic recovery, including analysis of the new hydrologic record for signatures of the 1970 fire and post-fire treatments; (4) analysis of water sources, flow paths, and timing of water delivery, with emphasis on the Burns Creek subwatershed where the most complete historical record exists; and (5) with improved understanding of catchment hydrology, evaluating hydrologic change associated with current land management practices, including fuels treatments, and transportation network management. Results will serve as a platform for virtual experiments simulating fire under current conditions. In future work we will use eleven other gaged catchments in the Entiat River subbasin to form the basis for nested hydrologic monitoring in this portion of the ICRB.

APPROACH

Following methods in McDonnell and Vache (in press), we are taking a diagnostic gaging approach to understand internal catchment behavior and develop a functional characterization of the EEF catchments. We are identifying first-order controls on hydrologic processes and investigating how these are linked to produce runoff at the subwatershed scale. This leads to a simple model structure that corresponds directly to the basic conceptual understanding of the catchment hydrology to test thinking about hydrologic processes and process linkages. Model structure and instrumentation are being developed concurrently to determine what to measure, where, and in what order. This approach to functional characterization of a catchment can be described in five steps (McDonnell and Vache in press) (Figure 2):

1. ***Field reconnaissance to investigate process scales*** – the representative elementary watershed (REW) is identified. This is the minimum catchment area at which hydrologic processes are representative of a larger scale. Determination of this area is commonly done through dilution gaging at a large number of tributary junctions to look for a relatively constant relationship between runoff rate and catchment size. At this threshold scale larger basins can be thought of as superpositions of smaller units.

2. ***Delineation of the dominant runoff producing zones and processes*** – these are represented as reservoirs in conceptual box models. These zones can be identified through longitudinal stream surveys using water temperature, conductivity, or pH as initial tracers. Anomalies at tributary junctions indicate reservoirs with different residence times, subsurface storage volumes, or exposure to disturbance.

3. ***Development of a simple, lumped, conceptual model to test thinking about catchment processes and characterize first-order process controls (Figure 3).*** This approach can incorporate "soft data" or qualitative knowledge of catchment behavior, such as the proportion of the catchment subject to saturation. Commonly this is knowledge that cannot be used as direct numbers,

Figure 2. A diagnostic approach to understanding internal catchment behavior and developing a functional characterization of catchment hydrology (McDonnell and Vache, in press).

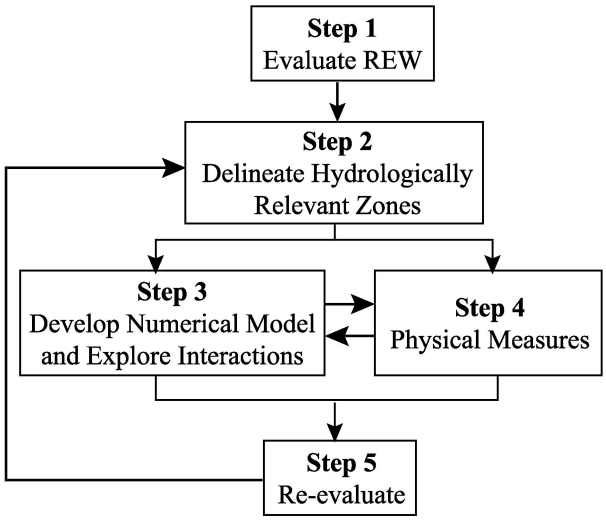
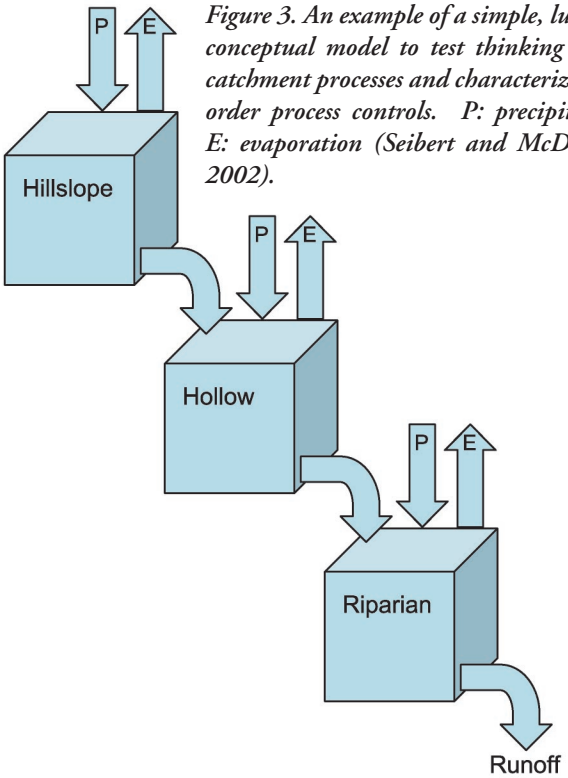


Figure 3. An example of a simple, lumped, conceptual model to test thinking about catchment processes and characterize first-order process controls. P: precipitation, E: evaporation (Seibert and McDonnell 2002).



but can be used as fuzzy measures of model simulation and parameter value acceptability. This injects some experimentalist common sense into the calibration process, providing a more "real" model of the catchment that better captures the key processes controlling catchment response (Seibert and McDonnell 2002).

4. ***Physical measures and characterization of dominant runoff producing processes*** – reservoirs, pathways and constants are added to the simple box model. The developing model focuses further instrumentation, gaging, and watershed characterization. Results are used to explore and represent the dynamic nature of the system and provide a useful framework for gauging. Only fundamental controls on hydrologic processes are included. The emphasis is on realistic internal dynamics, rather than forcing model efficiency. This step can include feedback to step 3, and acts as a springboard to more complex approaches. Visual modeling software is useful for this step. Figure 4 provides an example from McDonnell and Vache (in press) of an application from another study area.

5. ***Develop more complete measurements and understanding of runoff processes including more detailed characterization of flow sources, pathways, and ages.*** This can include: more rigorous gaging including at tributary junctions, quantification of details of runoff response to rainfall, identification of thresholds in reservoir connections, and analysis of stream and groundwater chemistry to characterize water source areas and residence times. Improved understanding may force re-evaluation of earlier models.

To further understanding of internal catchment behavior we will install a series of nested discharge measurement stations to assess longitudinal contributions of groundwater to stream discharge, thereby delineating dominant runoff producing zones and processes. We will further analyze water sources and pathways using tracers, including water temperature, conductivity, and others (McDonnell and Tanaka 2001). Analyses of stable isotopes, in particular ^{18}O, in stream water can be extremely valuable in defining water age. This allows determination of the proportion of "old" vs. "new" water in runoff and leads to definition of runoff sources and flowpaths. The role of physiographic and landscape characteristics in the composition of water will be assessed following the approach of McGlynn et

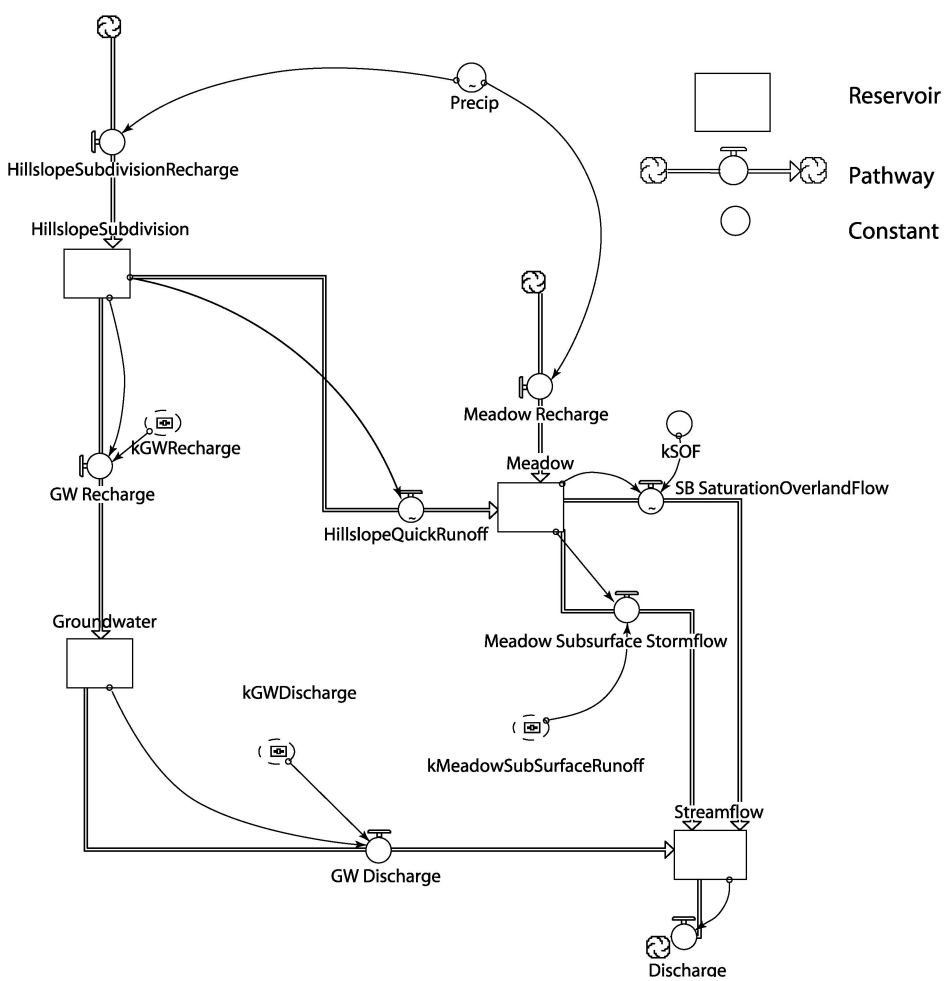


Figure 4. An example of a refined conceptual model of runoff processes using "STELLA" (High Performance Systems Inc.)[1] visual modeling software (McDonnell and Vache 2004). Details in this example are not relevant to the Entiat study area.

1 The use of trade names is for the information and convenience of the reader. Such use does not constitute an official endorsement by the U.S. Department of Agriculture of any product to the exclusion of others that may be suitable.

al. (2003), who found that streamwater composition was controlled by the distribution of tributaries, related sub-catchment area, and the associated mean water residence time of each. Distinctions among water sources, flowpaths, and ages have important implications in assessment of the effects of disturbance including fire. For example, studies in other areas have indicated that the majority of runoff can be "old" groundwater, rather than storm event water, implying that immediate effects of disturbance may be strongly damped by the influx of pre-disturbance water, possibly from other parts of the catchment.

The HBV Model

We are employing the Hydrologiska Byråns Vattenbalansavdelning [HBV] rainfall-runoff model (Bergstrom 1995) as a tool for change detection, whereby the effects of the 1970 fire will be assessed through the gaging record. We use EEF field data to make the HBV model more distributed and more tailored to the specifics of the EEF catchments, following methods of Seibert and McDonnell (2002). Early post-fire and current gage data will be analyzed to see if change can be detected relative to the 1960s pre-fire condition. HBV is a simple, conceptual model for runoff simulation, which is widely used in Nordic countries. It is semi-distributed in that it accommodates division into sub-catchments and elevation and vegetation zones. HBV lends itself to conceptualization of a catchment as a series of linked reservoirs that can be represented as boxes in simple flow diagrams (Figure 5) (Seibert 1996).

The HBV model simulates daily discharge using daily rainfall, temperature, and potential evaporation as input. Rainfall and temperature values are the weighted means among stations and are corrected for elevation by zone. Potential evaporation estimates are normally monthly mean values based on the Penman formula or evaporimeters. The long-term mean of the potential evaporation for a certain day can be corrected to its value at day t by using deviations in temperature from its long-term mean and a correction factor (Seibert 1996).

Precipitation is simulated to be either snow or rain depending on whether the temperature is above or below a threshold temperature (TT). All precipitation simulated to be snow (that falling when the temperature is below TT) is multiplied by a snowfall correction factor to account for losses to evaporation and sublimation and measurement error, which tends to be greater than for rainfall measurement. Typical correction factor values for forested areas are about 0.8. Snowmelt is calculated using a simple degree-day method. Meltwater and rainfall are retained within the snowpack until they exceed a certain fraction of the snow water equivalent. Liquid water within the snowpack refreezes according to a refreezing coefficient applied to TT (Seibert 1996). The refreezing coefficient, snowfall correction factor, and TT are adjustable model parameters, rather than empirically derived quantities.

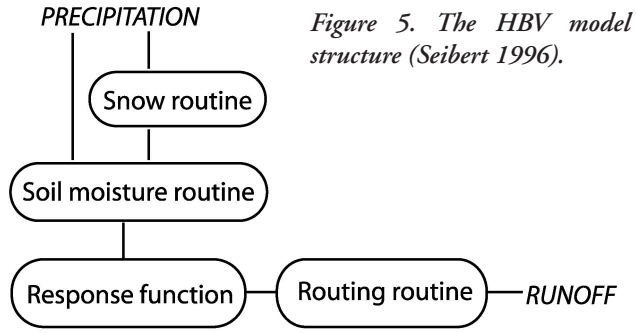


Figure 5. The HBV model structure (Seibert 1996).

Submodel	Input data	Output data
Snow routine	Precipitation, temperature	Snow pack, snowmelt
Soil routine	Pot.Evap., precipitation, snowmelt	Act.Evap., 'soil moisture', groundwater recharge
Response function	Groundwater recharge, (pot. ET)	Runoff, 'Groundwater level'
Routing routine	Runoff	Simulated runoff

Rainfall and snowmelt (P) are divided into water filling a conceptual soil box and groundwater recharge depending on the relation between water content of the soil (SM), its largest value, field capacity (FC), and the parameter 'Beta'. At low soil moisture all rain and snowmelt goes to soil moisture storage. At field capacity (maximum soil moisture storage), all rain or snowmelt goes to groundwater recharge (Figure 6). Actual evaporation from the soil box equals potential evaporation if SM/FC is above LP, while a linear reduction is used when SM/FC is below LP (Figure 7) (Seibert 1996).

Groundwater recharge is added to an upper groundwater box or reservoir. From there water percolates to a lower groundwater box at a maximum rate. Runoff from the groundwater boxes is computed as the sum of two or three linear outflow equations depending on whether or not recharge in the upper groundwater box is above a threshold value. Outflow at time t is proportional to water storage (S) as determined by the coefficient "k" (Figure 8). The first estimate of the groundwater response parameter (k) is taken from the slope of hydrograph recession curves. Finally, simulated groundwater outflow is transformed

Figure 6. The HBV soil moisture routine – contributions from rainfall or snowmelt to soil moisture storage and to the upper groundwater zone. FC is the maximum soil moisture storage, BETA is a parameter that determines the relative contribution to runoff from rain or snowmelt (Seibert 1996).

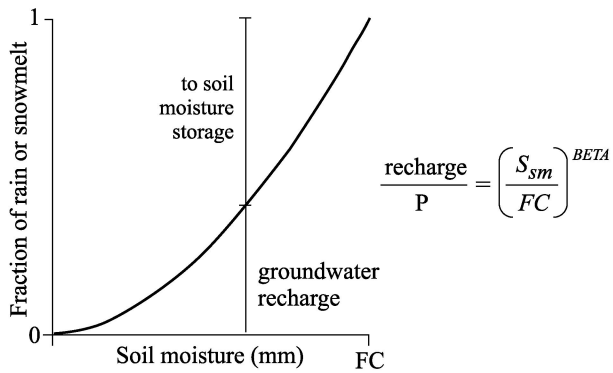
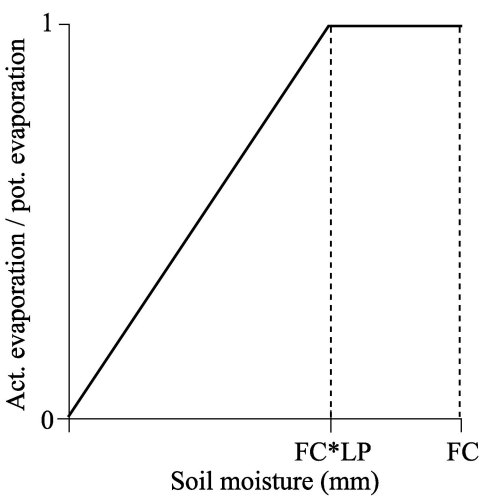


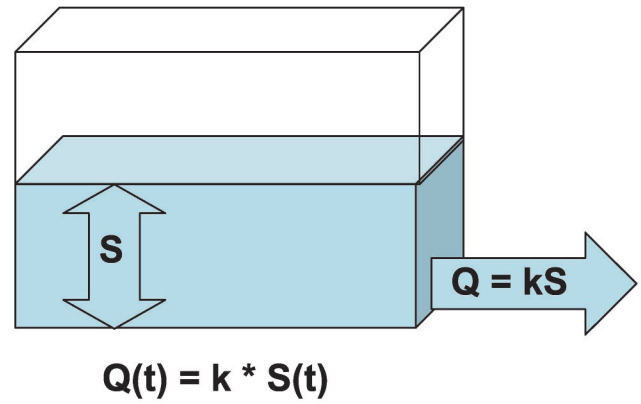
Figure 7. The HBV model – change in actual evaporation depending on soil moisture storage. FC is a model parameter and not necessarily equal to measured values of 'field capacity'. LP is the soil moisture value above which actual ET reaches potential ET (Seibert 1996).



to simulated catchment runoff by a weighting function, which distributes runoff from one time step onto the following days (Seibert 1996).

Distributions of reasonable parameter values are developed using a Monte Carlo approach. Parameter values are chosen randomly within a specified range for each run, and a large number of model runs, each generated by a distinct parameter set, are performed. Working with a set of parameters, rather than a single value, allows computation of parameter confidence intervals and reduction in parameter uncertainty (Seibert 1997). Best fit parameter sets are selected through an assessment of the fit of simulated to observed runoff data based on visual inspection of fit, accumulated difference between

Figure 8. The HBV model – simple linear reservoir response function. The model of a single linear reservoir is a simple description of a catchment where the runoff Q(t) at time t is proportional (k) to the water storage S(t) (Seibert 1996)



simulated and observed values, and statistical criteria. Commonly, the coefficient of efficiency is used to evaluate model fit. This coefficient compares the prediction by the model with the simplest possible prediction, a constant observed mean value over the period. Alternatively multiple objective functions can be used, with measures combined through fuzzy logic algorithms (Seibert 1996; Seibert 1997).

APPLICATION OF THE HBV MODEL

We employ the HBV model to evaluate hydrologic change in the EEF data (Seibert et al. 2004), and report preliminary results here to illustrate the approach. Publication of final results is forthcoming. Change was evaluated by: (1) comparing runoff simulated from pre-fire parameter sets to observed runoff (simulation vs. observation); (2) comparing simulations based on pre-fire parameter sets to simulations based on post-fire parameter sets (simulation vs. simulation); and (3) directly contrasting pre-fire with post-fire parameter values. The simulation vs. observation approach involves calibrating parameter sets using pre-fire data, simulating pre- and post-fire runoff from these parameter sets and driving variables, then contrasting simulated to measured runoff. This is done by contrasting the statistical central tendency and dispersion of residual (observed minus simulated) distributions for the larger peak flows. Dispersion of this distribution provides a measure of parameter uncertainty. The simulation vs. simulation comparison is done by calibrating separate parameter sets for pre- and post-fire runoff data. Separate simulations of the larger post-fire runoff events are run for these parameter sets using post-fire driving variables. Simulated values are then compared to a hypothetical

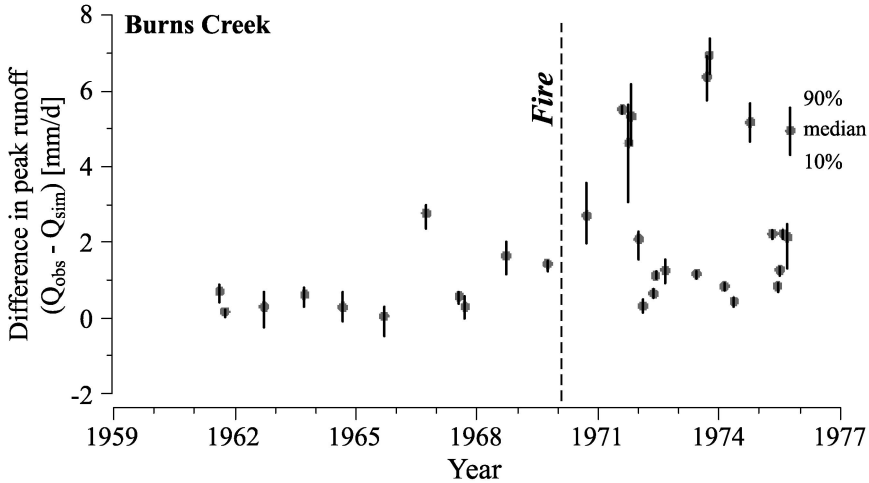


Figure 9. Observed minus simulated runoff based on pre-fire parameter sets. Severe fire occurred on 24 August 1970. Data points are median values of the 100 best-fit parameter sets. Vertical bars represent the corresponding distribution of runoff values (Seibert et al. 2004).

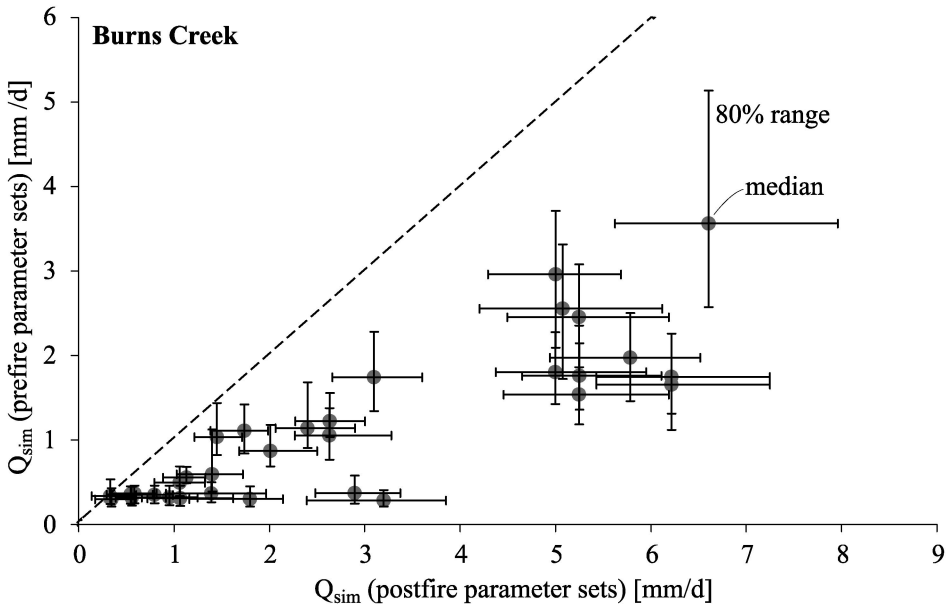


Figure 10. Post-fire runoff simulated from post-fire parameter sets vs. pre-fire parameter sets. Data points are median values of the 100 best-fit parameter sets. Bars represent the corresponding distribution of runoff values (Seibert et al. 2004).

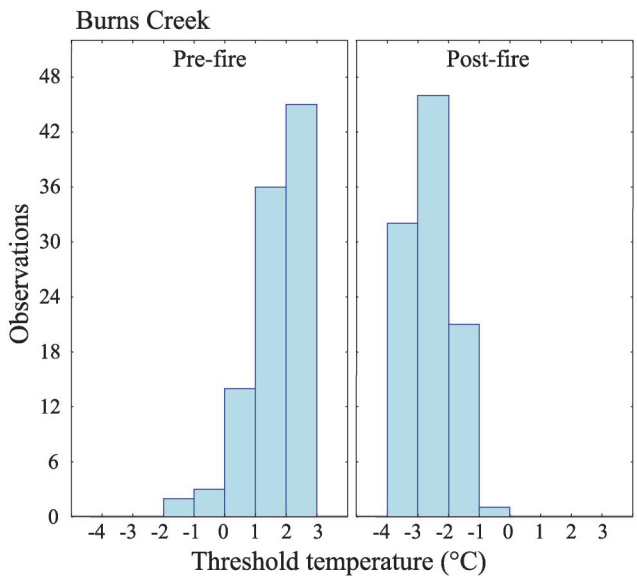
zero-change result. To directly contrast pre- with post-fire parameter values, separate parameter sets are calibrated, then pre- and post-fire values of central tendency of each parameter are contrasted (Seibert et al. 2004).

Each of these three approaches was applied to the EEF data. One million model runs were performed, and the 100 best fit parameter sets selected from these. The simulation vs. observation approach indicated a general increase in post-fire median runoff (Figure 9). Error bars in Figure 9 indicate distribution in runoff among the 100 best-fit parameter sets. Similarly, the simulation vs. simulation approach indicated a consistent increase in post-fire runoff (Figure 10).

Pre- and post-fire parameter sets were directly compared for all three EEF subwatersheds. Results indicated post-fire increases in soil moisture, reducing available storage for storm event water by approximately half. Modeling further indicated a 50% increase in the snowfall correction factor, implying greater snow accumulation, a 3°C post-fire decrease in temperature threshold (Figure 11), implying onset of snowmelt approximately one-month earlier than normal for the pre-fire period, and a 50% increase in rate of snowmelt calculated by the degree-day algorithm. These changes combined to produce modeled post-fire peak flow increases of 100% or more (Seibert et al. 2004). Our modeling results are in general agreement with findings of Helvey (1980) based on a conventional paired watershed approach, using the Chelan River as a control. Helvey computed measured minus predicted runoff based on pre-fire calibration, and determined that post-fire annual runoff increased from 1.7- to 3-fold relative to the pre-fire mean.

Although validation of the physical basis for these changes in adjustable parameter values is beyond the scope of this paper, the modeled shifts in values are physically reasonable. Fire related reduction in evapotransporation

Figure 11. Distribution of the threshold temperature (TT) parameter among the 100 best-fit pre- and post-fire parameter sets (Seibert et al. 2004).



should increase soil moisture; reduced canopy interception should lead to greater snow accumulation; and increased turbulent exchange at the snow-air interface should increase the efficiency of snowmelt processes leading to initiation of runoff at lower mean air temperatures (earlier in the season) and higher rates of snowmelt.

Summary

In recent years interest in the hydrologic recovery of burned areas has increased. Effects of fire on soil and vegetation can lead to increased runoff, peak flows, flooding, water yield, erosion, sediment load, turbidity, mass soil movements, and debris flows that alter water quantity and quality and may threaten human life and property (Beschta 1990; Conedera et al. 2003; DeBano et al. 1998; Meyer et al. 2001; Robichaud et al. 2000; Swanson 1981; Tiedemann et al. 1979; Wells et al. 1979; Wondzell and King 2003). Despite increased interest, few data exist at the subwatershed scale that document the effects of wildfire on runoff characteristics. The EEF is the site of one of very few published studies that chronicle a "natural fire experiment" before and after wildfire.

Our objectives are to review and expand upon previous analyses of existing hydrologic data and to renew data collection and analyses in the EEF. We seek to increase understanding of the effects of severe wildfire and post-fire land management on water quantity, quality, and timing, as well as long-term hydrologic recovery following severe disturbance such as fire. Increased predictive capability regarding effects of severe wildfire and mechanisms and rates of hydrologic recovery will inform land management responses to these events. For example, improved knowledge of long-term hydrologic recovery following wildfire could help guide decisions regarding the relative value and advisability of various post-fire rehabilitation approaches. Increased understanding of catchment hydrology at the subwatershed scale will improve evaluation of hydrologic change associated with a variety of land management practices. Availability of gaging records for the Entiat River subbasin creates an opportunity to scale up this new knowledge from the subwatershed scale to larger areas within the ICRB.

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