Impacts of Forest Management on Runoff and Erosion

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Abstract

In a parallel study, ten small watersheds (about 5 ha) were installed in the Priest River Experimental Forest (PREF) in northern Idaho, and another ten were installed in the Boise Basin Experimental Forest (BBEF) in central Idaho. The long-term objective of the study is to compare the effects of different forest management activities on runoff and sediment delivery. This paper reports the observed runoff hydrographs and amounts and the sediment yields during the first 3 to 4 years of the study. During the first 3 years, none of the watersheds received any management treatments or natural disturbances. In the autumn of year 3, a simulated wildfire was carried out at four watersheds in PREF. There was still no runoff from these four watersheds the spring following the fire. These observations will be useful for evaluating the natural variability in hydrologic responses on forest landscapes.

Of the ten sites in PREF, one generated perennial runoff (averaging 231 mm of runoff from 783 mm of precipitation), and one generated only spring runoff averaging 13 mm from 732 mm of precipitation. The other 8 plots generated no runoff. Only the watershed with continuous flow generated any sediment. It averaged 6 kg/ha. In the BBEF study, four to six of the ten watersheds generated seasonal runoff, depending on the year's weather. Of the plots that generated runoff, the average runoff was 34 mm from 555 mm of precipitation. The average sediment yield was less than 1 kg/ha.

Keywords: forest, watershed, hydrology, research

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Introduction

Our forests are sources of numerous ecosystem services, one of which is clean water. The greatest pollutant of forest streams is sediment. Undisturbed forests generally do not generate sediment, but natural disturbances, such as wildfire or extreme weather events, or human disturbances, such as logging, thinning, prescribed fire, or roads, generally result in an increase in sedimentation from forest watersheds.

In order to estimate the sediment generated from natural or human disturbances, research studies are carried out at plot and watershed scales. Gaged watersheds can vary in size from one or two hectares to thousands of square kilometers. Generally, research watersheds are restricted to less than several hundred hectares to allow researchers to more carefully evaluate effects of specific management activities on watershed response.

One of the properties of forested watersheds is the high level of spatial variability within the watershed. Variability is due to differences in geology, soils, aspect, slope, and vegetation. Prescribed burns and wildfire lead to high variability in the groundcover remaining to protect the mineral soil from raindrop splash and runoff. The amount of cover remaining depends on the amount present before the fire, the water content of the litter, and the severity of the fire (Robichaud 1996).

Forest management has changed in recent years. Effects of logging are much less severe on watersheds due to current logging practices, e.g., leaving buffers around stream channels, locating roads away from streams, limiting the number of skid trails, using low ground pressure skidders, or using forwarders to transport logs (Karwan et al. 2007). Prescribed fire and thinning are becoming more common, particularly in the wildland urban interface (WUI), to remove excess fuels, reduce the risk of wildfire spread, and increase the effectiveness of fire suppression. Managers need to evaluate the watershed effects from these low-impact activities.

There are two main approaches to forest watershed research. One approach is to use paired watershed studies. With paired studies, "similar" watersheds are identified and monitored for 5 to 10 yrs with no treatment. The runoff amounts and sediment yields are collected from the two watersheds and the differences are noted. One of the pair is then treated and the other is left untreated. In the years following the treatment, the differences between the two watersheds are once again measured, and the researcher evaluates any change in differences between the pair and assumes that the change reflects the treatment effects.

The second approach for many watershed studies is to install "nested" watersheds, a smaller watershed monitored within a larger watershed. Sometimes a paired watershed study may be nested within a large watershed (Hubbart et al. 2007). The purpose of the nested approach is to evaluate the effect of a treatment in the smaller watershed at ever increasing scales.

Both of these study designs are dependent on watersheds with similar properties. The degree of similarity, however, may be difficult to predict. If sites are identified during dry seasons, or during wet seasons, there may be no apparent differences, but during critical times mid-season, one watershed may continue to generate runoff and sediment for several weeks after an adjacent one has ceased to flow.

A common practice following wildfire is to carry out a "salvage logging" operation, where fire-killed trees are harvested to obtain at least some economic return from the burned forest and reduce fuel loading and future fire risk. The watershed impacts of salvage logging are not known (Beschta et al. 1995), and there is a need to carry out a number of studies of salvage logging impacts under different conditions.

In order to reduce the risk of wildfire, a common forest practice is to carry out thinning with or without prescribed fire (Graham and Jain 2005). These activities tend to be low impact, but little information is available of the impact of such operations.

There is a need to understand variability between watersheds, to better evaluate observations from paired and nested watershed studies. There is also a need to evaluate the impacts of current forest management practices on runoff and sediment delivery from forest watersheds.

The specific objectives of this paper are:

1. To describe a study that measures the watershed impacts of current forest fuel management practices including wildfire and salvage logging, and
2. To present the runoff and erosion rates from these watersheds observed during the first 3 to 4 yrs in order to evaluate natural variability and fire effects in small watershed studies.

Methods

Research sites

In order to evaluate the variability in small forest watershed studies, ten small watersheds were installed in each of two experimental forests managed by the U.S. Forest Service Rocky Mountain Research Station. One location was in the Priest River Experimental Forest (PREF) located in the Idaho Panhandle National Forest about 20 km north of the Priest River, ID. The other location was in the Boise Basin Experimental Forest (BBEF) located about 80 km northeast of Boise, ID, in the Boise National Forest (Figure 1).

The soils on the PREF "are categorized within the Typic Vitrandepts soil complex. These soils have a thick mantle of volcanic ash-influenced loess from Cascade volcanoes overlaying belt series parent material. Variations within the major soil complex are dependent on elevation, slope, aspect, and topographic position" (Schmidt and Friede 1996, p. 53). In the BBEF, "soils are derived from granitic rocks of the Idaho Batholith. The rocks are mostly quartz monzonite with some porphyritic and aplitic dikes. The soils are generally deep except on extremely steep slopes and ridges and are mostly coarse to moderately coarse in texture. Representative soils are mostly Typic or Lithic Xeropsamments, Cryumbrets, Cryoboralls, Cryorthents and Cryochrepts" (Schmidt and Friede 1996, p. 42).

At PREF, four of the watersheds were in western red cedar (*Thuja plicata*) and six were in grand fir (*Abies grandis*) habitat types. Time since last harvesting or thinning operations varied from 10 to 100 years. The watersheds experiencing the more recent (about 10 years) thinnings were selected for control treatments.

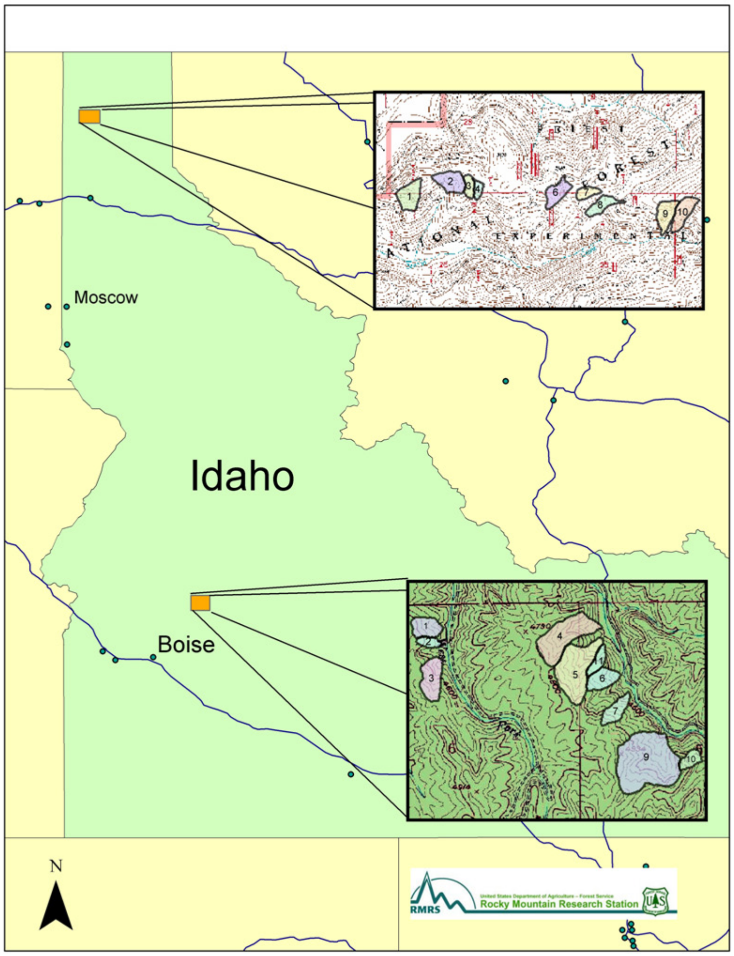

Figure 1. Location of Priest River (top/north) and Boise Basin (bottom/south) Experimental Forests.

These watersheds would not easily carry wildfire, nor did they have vegetation in need of thinning. None of the watersheds had experienced harvesting in the past 50 years. Interior ponderosa pine (*Pinus ponderosa*) is the predominant forest cover type on the BBEF experimental forest (Schmidt and Friede 1996). In the BBEF, none of the watersheds have been disturbed by fire, thinning, or harvesting in the past 50 years. Prior to that, the watersheds appeared to have been clear cut harvested as the stands were uniform in age.

Treatments

The same study plan was used by installing ten small watersheds at both PREF and BBEF to facilitate statistical analysis (Tables 1, 2). Each site had two main treatments, simulated wildfire (four watersheds) and thinning (four watersheds), as well as an undisturbed control (two watersheds) for a total of ten. Following the wildfire treatment, two of the wildfire plots are treated with a salvage logging operation to remove large trees with economic value. Following the thinning, two of the thinned plots are treated with a mastication operation, shredding the slash, young tress, and other short growing vegetation. The other two thinned plots will be treated with a prescribed fire to remove slash and reduce short vegetation. Treatments were selected to suit the vegetation condition of each watershed. For example, watersheds in least need of treatment to minimize wildfire risk were chosen as controls. Adjacent watersheds were selected for the wildfire treatments to minimize the amount of fire line that would have to be dug prior to the wildfire treatment. Watersheds with merchantable timber were selected for thinning to increase the chance of completing a timber sale (Graham and Jain 2005).

Watersheds

The watersheds to be treated with simulated wildfire were all under 5 ha. A number of wildfire and fuel management treatments have been completed on watersheds of this size (e.g., Covert et al. 2005, Robichaud 2005), so keeping a similar size makes observations from our studies easy to compare to a number of studies of similar scale with similar erosion and sedimentation processes.

At Priest River, the watersheds were all south or southwest facing (Figure 2). Outlet elevations ranged from 841 m on the west to 1,040 m on the easternmost watershed (Table 1). Areas ranged from 1.7 ha to 6.5 ha, with the smaller watersheds used for the wildfire treatments. Average slopes ranged from 21 to 43 percent. One weather station was installed near watershed 2 to provide lower elevation weather data, and a second weather station was installed near watershed 7. All of these watersheds drain into Benton Creek. Watersheds 9 and 10 are upstream from a weir that has been monitoring flow for 70 years.

The Boise Basin watersheds have an east-northeast aspect and are located on two adjacent ridges (Figure 3), so there is a smaller range of elevations (Table 2). Outlet elevations ranged from 1,338 m to 1,424 m. The watershed areas ranged from 0.9 ha to 12.2 ha. The largest watershed (9) was used as a control to minimize the risk of overwhelming the outlet flume. The wildfire watersheds were smaller. Average slopes ranged from 24 to 46 percent. Watershed 8 was originally intended to be one of the wildfire treatment watersheds. Following installation, however, the Forest Service fire management specialist determined that it would be difficult to contain a "simulated wildfire" on this small watershed, and there was a risk that the fire could spread to the large control watershed 9. The following year, an additional watershed, number 11, was installed to use instead of watershed 8 for the wildfire treatment. Hence, watershed 8 is not listed in Table 2, but the outlet structure is still in place. A single weather station was considered to be sufficient for this site because there was not a large variation in elevation among the watersheds.

Groundcover was measured on all the watersheds following methods developed for measuring fire severity to support ground truthing for satellite imagery (Hudak et al. 2007). A 60-m grid was established to reference groundcover and vegetation response to treatments. At each grid point, a tape was extended in a random direction, and four measurement points at a 10-m spacing along a linear transect were defined. At each measurement location, a 1-m^2 frame with 100 points was placed on the ground and the material beneath the grid recorded. Material classes were mineral soil, ash, rock, woody material, organic material, and charcoal. The number of points in each class was converted to a percent and averaged for each watershed.

Outlet structures

For the control, thinning, and thinning plus prescribed fire plots, metal borders were installed at the bottom of each plot to divert the runoff water to a 300-mm pipe. The pipe conveys the water to a large covered 1-m^3 plastic box that serves as a sediment trap (Figure 4). The outflow from the trap is diverted to a 2-m long fiberglass trough leading to a 1-ft nominal fiberglass H-flume with a stilling basin. Flow depth in the H-flume is measured with a Magnerule™ and recorded at 30-min intervals on a nearby data logger (Figure 4).

The wildfire sites are designed similarly to those used in other wildfire erosion studies (Robichaud 2005). A 2-m-high sheet metal and wood post barrier was installed on one of the watersheds destined for a wildfire treatment in the Boise Basin Experimental

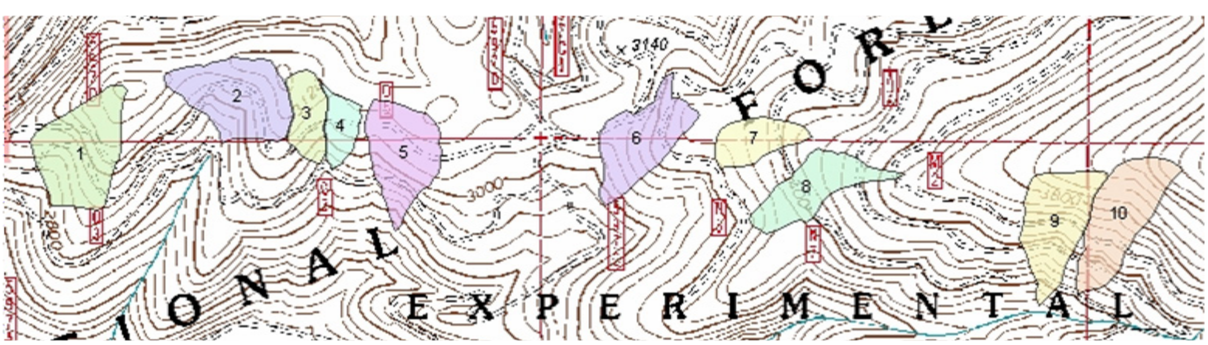

Figure 2. Locations of the watersheds in the Priest River Experimental Forest.

Figure 3. Location of watersheds in the Boise Basin Experimental Forest.

Figure 4. Sediment box and flume for control and thinned plots at the Boise Basin Experimental Forest.

Figure 5. V-notch weir and headwall on one of the watersheds destined for a wildfire treatment in the Boise Basin Experimental Forest.

Forest across the watershed outlet. A 300-mm 90° V notch was cut in the sheeting to serve as a V-notch weir, approximately 1.5 m above the elevation of the existing waterway (Figure 5). Following a major erosion event, the erosion can be estimated by measuring the accumulated volume of sediment, if it is large, or by excavating all of the deposited sediment and weighing it by the bucket until the collection basin is empty (Robichaud 2005).

Simulated wildfire, salvage logging, and thinning

To simulate the effects of a wildfire, trees that were likely to be killed by a wildfire were selected in each plot (Graham and Jain 2005). The selected trees were girdled in the summer before the fire. Local Forest Service fire crews burned PREF watersheds 3, 4, 7, and 8 in October 2006, and BBEF watersheds 6, 7, 10, and 11 in June 2008. A fire break was manually dug around each watershed and a fire hose laid around the perimeter prior to burning. Each watershed was then ignited with propane torches around the perimeter, from the top to the bottom. Instrumentation was protected with fire blankets and dampened to prevent damage (Figure 6).

Results

The runoff amounts from the watersheds are presented in Tables 1 and 2. During 2004, installation problems and low batteries at both the PREF and BBEF sites resulted in data loss. There was sufficient information, however, to determine which watersheds generated runoff and which did not. The equipment malfunctioned during the main spring runoff events on these watersheds, likely a result of freezing.

At PREF there were only two watersheds that generated any runoff (Table 1). Watershed 6 had runoff during the spring snowmelt season, and watershed 10 had runoff throughout the year, including midwinter when the watershed was covered in snow and late summer when the site had not experienced significant precipitation for several months.

For the BBEF sites (Table 2), there was runoff observed from watershed 9 in 2004, watersheds 1, 2, 5, and 9 in 2005, and watersheds 1–5 and 9 in 2006.

The average precipitation for the PREF sites was 729 mm, and for the BBEF site 513 mm (Table 3). The

BBEF gage did not function from Jan. 1 until April 30 in 2007, so data from the nearby Garden City Ranger District was used as an estimate. At PREF, the lower gage (elevation 883 m) averaged 708 mm, whereas the higher elevation gage (989 m) averaged 751 mm during the 3 yrs of observations.

The average annual temperature was 12.2ºC for PREF and 6.8ºC for BBEF (Table 4). At the BBEF site, the temperature data sensors malfunctioned between Jan. 1 and May 18, 2005, and between June 1 and Sept. 19, 2006. For these dates, data from the Idaho City weather station (elevation 1,201 m), 5.2 km northwest of the site, were used.

Pre-disturbance groundcover observed at PREF was 98 to 100 percent on all watersheds except watershed 9 that had 96 percent cover (Table 5). At BBEF groundcover was between 90 and 100 percent (Table 6), averaging 96 percent. The groundcover was mainly decomposing organic material (83–95 percent) and woody material (4–17 percent).

The hydrographs from some of the watersheds were drawn to ascertain differences in the timing of the runoff. The hydrographs from the small watersheds were compared to nearby watersheds to see how well the small watershed reflected the response of watersheds at a large scale. In the PREF, two of the watersheds were nested within the Benton Creek drainage, which has been monitored since the 1930s. The Benton Creek Watershed has an area of 385 ha and is entirely forested (Stage 1957). The range of elevations on the research watersheds (841–1,270 m) is similar to the elevation within the Benton Creek watershed (810–1,679 m). The ten research watersheds are located at mid-elevation in this watershed. In the BBEF, a nearby watershed, Mores Creek, has a U.S. Geological Survey (USGS) gauging station (U.S. Geological Survey 2007). The area above the Mores Creek gage is 103,385 ha and is predominantly forested. The BBEF plots are similar in elevation to the midlevel elevation of Mores Creek. Figure 7 shows the hydrographs for two small watersheds at PREF and two at BBEF, as well as the hydrographs from the nearby large watersheds.

Only two watersheds generated any sediment during the 3 yrs of observation (Table 7). The observed sediment yields were very low (under 10 kg ha^{-1}), and appeared to be coming from the channel. No erosion features were observed on the hillslopes.

Figure 6. Protecting the instrumentation with fire blankets and water during the simulated wildfire at the Priest River Experimental Forest in October 2006.

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Table 1. Details of watersheds in the Priest River Experimental Forest.

Watershed	Tmt*	Area (ha)	Avg. slope (%)	Elev. (m)	Observed runoff for year (mm)			
					2004	2005	2006	2007
1	Thin/Mast	6.5	30	857	0.0	0.0	0.0	0.0
2	Thin/Mast	6.2	27	878	0.0	0.0	0.0	0.0
3	Burn	2.4	21	890	0.0	0.0	0.0	0.0
4	Burn/Salv	1.7	21	890	0.0	0.0	0.0	0.0
5	Thin/Burn	5.3	28	841	0.0	0.0	0.0	0.0
6	Control	5.1	21	902	RO**	14.1	11.5	46.3
7	Burn	2.6	27	988	0.0	0.0	0.0	0.0
8	Burn/Salv	4.2	27	988	0.0	0.0	0.0	0.0
9	Thin/Burn	5.5	43	1,012	0.0	0.0	0.0	0.0
10	Control	5.9	41	1,040	RO**	196.5	248.9	248.9
Average		**4.5**	**29**	**929**				

* Watershed treatment.
** On these plots, runoff (RO) was observed in 2004, but the amount was not measured.

Table 2. Details of watersheds in the Boise Basin Experimental Forest.

Watershed	Tmt*	Area (ha)	Avg. slope (%)	Elev. (m)	Observed runoff for year (mm)		
					2004	2005	2006
1	Thin/Mast	2.2	29	1,354	0.0	RO**	15.7
2	Thin/Burn	0.9	35	1,357	0.0	RO**	3.1
3	Control	3.2	30	1,357	0.0	0.0	11.6
4	Thin/Mast	6.4	24	1,338	0.0	0.0	16.2
5	Thin/Burn	7.0	27	1,351	0.0	RO**	123.4
6	Burn/Salv	2.1	40	1,357	0.0	0.0	0.0
7	Burn	1.9	46	1,363	0.0	0.0	0.0
9	Control	12.2	26	1,387	RO**	RO**	34.3
10	Burn/Salv	1.2	37	1,424	0.0	0.0	0.0
11	Burn	1.2	34	1,363	0.0	0.0	0.0
Average		**3.8**	**33**	**1,365**			

* Watershed treatment.
** On these plots, runoff (RO) was observed but the amount was not measured accurately.

Table 3. Observed annual precipitation at the Priest River (PREF) and Boise Basin (BBEF) Experimental Forests.

Station			Year and precipitation (mm)				
PREF	Applies to watersheds	Elevation (m)	2004	2005	2006	2007	Avg
Weather 1	1–5	883	736.6	672.6	786.9	636.5	708.2
Weather 2	6–10	989	795.0	760.7	794.8	651.8	750.6
BBEF							
Weather 1	All	1,363	partial year	595.4	514.4	430.3	513.4

Table 4. Average annual daily temperatures for the Priest River and Boise Basin research sites.

	Elev (m)	Average temperature (ºC)			
		2005	2006	2007	Average
PREF					
Weather1	883	14.0	14.8	14.4	14.4
Weather2	989	10.0	10.5	10.7	10.4
BBEF					
Weather1	1,363	6.5	6.7	7.1	6.8

Table 5. Groundcover observations (percentage) prior to any disturbance on the Priest River Experimental Forest watersheds.

	WS1	WS2	WS3	WS4	WS5	WS6	WS7	WS8	WS9	WS10
Mineral Soil	2	1	0	0	0	1	0	0	4	0
Ash	0	0	0	0	0	0	0	0	0	0
Rock	0	0	0	0	0	0	0	0	1	0
Woody matl.	4	4	17	10	15	13	15	12	10	5
Organic matl.	94	95	83	90	85	86	85	88	85	95
Charcoal	0	0	0	0	0	0	0	0	0	0

Table 6. Groundcover observations (percentage) prior to any disturbance on the Boise Basin Experimental Forest watersheds.

	WS1	WS2	WS3	WS4	WS5	WS6	WS7	WS9	WS10	WS11
Mineral soil	0	1	3	7	4	2	0	2	10	1
Ash	0	0	0	0	0	0	0	0	0	0
Rock	0	0	0	0	0	0	0	0	0	0
Woody matl.	15	5	8	4	9	12	16	10	2	9
Organic matl.	85	94	89	89	87	86	84	88	88	90
Charcoal	0	0	0	0	0	0	0	0	0	0

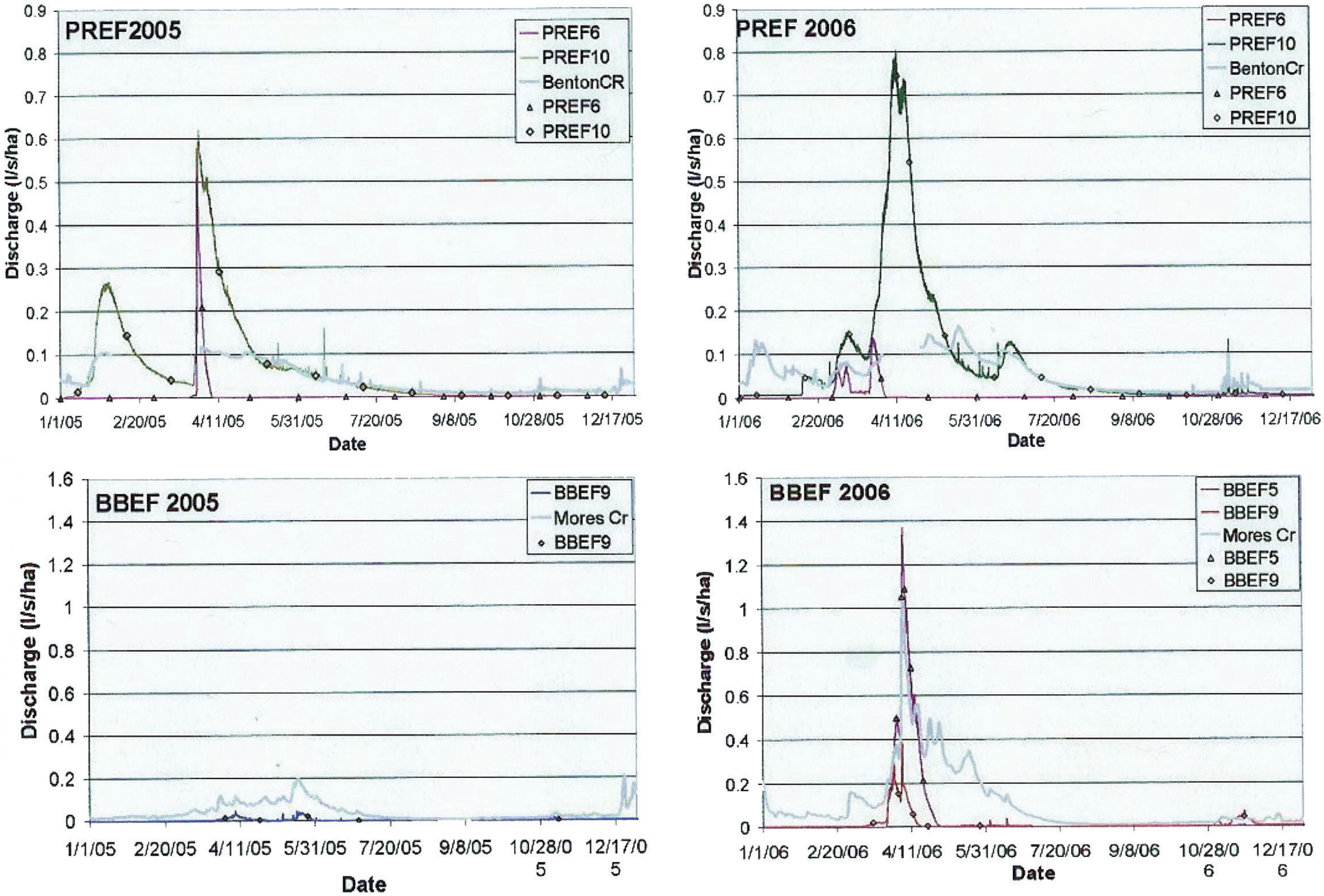

Figure 7. Hydrographs for 2005 and 2006 for selected small watersheds at Priest River and Boise Basin Experimental Forests compared to nearby larger watersheds of Benton Creek and Mores Creek, respectively.

Discussion

In the current condition, the watersheds are exhibiting a wide range of variability. Only two of the ten watersheds at PREF had any observed runoff, whereas six of the watersheds at BBEF had runoff. Even though the climate at BBEF is drier than at PREF (Table 3), there were more watersheds with runoff, likely due to the lower water holding capacity of the coarse textured soils at BBEF (Schmidt and Fried 1996). It is hypothesized that the one watershed at PREF that was generating significant runoff year round likely had a more shallow soil or less permeable bedrock. The geologic map of the area shows that the bottom quarter of watershed 10 was underlain by metamorphic rock that was not present in any of the other watersheds except the last few meters of watershed 9 (Miller et al. 1999). The soils at PREF are more variable than at BBEF (Schmidt and Friede 1996, Miller et al. 1999). Generally, the larger the watershed at BBEF, the more likely it is to generate runoff ($r^2 = 0.3$). This scaling effect on runoff was noted at a larger scale in a comparison of a 106-ha watershed to a 177-ha watershed by Zhang et al. (2009).

The BBEF site is 500 km south of the PREF site, but because of the higher elevation, is cooler (Table 4). As snowmelt dominates the hydrology on both of these sites (Figure 7), the importance of these temperature differences is an area requiring further investigation.

Table 1 shows that the ephemeral watershed at PREF (watershed 6) generated more runoff in 2005, even though there was less precipitation than in 2006. This is likely a reflection of high snowmelt rates that dominated runoff of this watershed because the majority of the runoff from this watershed occurred between March 23 and April 7, a duration of 15 days in 2005, compared to a melt period from February 28 until April 17 in 2006, a duration of 48 days. The perennial-flow watershed at PREF (watershed 10) generated 52 mm more runoff in 2006 than 2005, likely due to the 70-mm difference in precipitation. Also, watershed 10 has a higher elevation, which resulted in a greater depth of snow (Elliot 2007) and a prolonged snowmelt period (Figure 7). Although 2006 was wetter than 2005 at the PREF watersheds, at BBEF there was 81 mm less precipitation in 2006 than in 2005. This reduced precipitation in 2006 at BBEF is not reflected in the observed runoff values, which were greater in 2006 on four watersheds and less on only two. The reason for this unexpected response may be linked to the timing and rate of snowmelt.

The groundcover was greater at Priest River than at Boise Basin (Tables 5 and 6). This difference in cover is likely due to the higher precipitation amounts at PREF (Table 3). The cooler temperatures (Table 4) at BBEF may have resulted in reduced vegetation growth, which would also result in less accumulation of groundcover. The reduced groundcover at Boise Basin may have contributed to the higher observed runoff rates (Pannkuk and Robichaud 2003, Fangmeier et al. 2006, p 81). There may also be differences between the two vegetation types (Pannkuk and Robichaud 2003).

The hydrographs in Figure 7 show that the small watersheds in this study generate normalized runoff with higher peak flows during the spring snowmelt season than do the nearby larger watersheds, but they experience a much faster decline in the falling limb of the hydrograph. The peak flow rates occur in early April at both PREF and BBEF, so apparently the differences in elevation of the two forests are offset by the differences in latitude (48.3 vs. 43.7°N). At both sites, the nearby larger watersheds continue to discharge water from snowmelt at higher elevations and likely from groundwater seepage after the snowmelt season as well.

At PREF, the watershed with the perennial flow was the only watershed that generated any sediment. At BBEF, sediment was generated by only one of the watersheds (watershed 9), which also runs most of the year. BBEF watershed 9, however, was not the watershed generating the greatest depth of runoff. It was the largest watershed in the study (12.2 ha), and its channel is more likely to generate sediment than channels on the smaller watersheds. Zhang et al. (2009) made a similar observation on the effect of forest watershed size on sediment delivery with the channel from a 106-ha watershed generating 13 kg/ha/y compared to the channel from a larger 177-ha watershed, in which the smaller one was nested, generating 26 kg/ha/y. Onsite observations indicated that the sediment source was the channel and not the forested hillslopes.

The absence of runoff and erosion following the simulated wildfires at PREF was not expected. Some localized soil displacement was observed on watersheds 7 and 8, but no sediment was collected at any of the outlet weirs. Earlier observations at PREF had suggested that these soils resisted erosion, and this study confirms those observations.

Conclusions

Ten small watersheds (under 10 ha) have been installed in the Priest River Experimental Forest in northern Idaho, and another ten in the Boise Basin Experimental Forest in central Idaho. Differences in geology and climate between these two locations resulted in only two watersheds generating runoff at Priest River, compared to six at Boise Basin. Both total precipitation amount and the timing and rate of snowmelt runoff, affect the total runoff as well as the peak runoff rate and duration of runoff. The role of snowmelt processes on runoff characteristics warrants further investigation.

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