Potential Hydrologic Response to a Prescribed Fire on a Small Mountainous Watershed

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Abstract

Prescribed fire is often used to control invasive weeds, improve habitat, and deter wildfire. The Northwest Watershed Research Center plans to burn a heavily studied 26-ha watershed. This paper investigates the potential hydrological response to that prescribed fire. Changes in water repellency and infiltration capacity were assumed not to limit the low intensity snowmelt input to the basin. Percolation, subsurface flow and runoff during the first runoff season are influenced by the soil moisture deficit created by pre-burn vegetation conditions and will likely not be influenced greatly by the fire. A year of reduced evapotranspiration following the fire is necessary to reduce the soil moisture deficit and increase percolation beyond the root zone and subsurface flow to the stream. Results indicate significant changes in streamflow in this subsurface-flow-dominated watershed may not be observed until the second snowmelt season following the fire and could increase by 25%. These results are unlike watersheds dominated by overland flow and surface runoff where increased flows are more likely to occur during the first year following a fire.

Keywords: evapotranspiration, percolation, prescribed burn, runoff, rangeland

Introduction

Reintroducing fire as part of the natural cycle to control invasive weeds and improve habitat on rangeland is becoming an accepted practice where appropriate. Post-fire vegetation, water balance and streamflow responses, however, are not well understood. Many mid- to high-elevation watersheds of the semi-arid Intermountain West are ephemeral, being dominated by snowmelt, evapotranspiration and subsurface water flow. The Northwest Watershed Research Center (NWRC) conducted a series of studies on one such watershed, Upper Sheep Creek, which culminated in a ten-year water balance for the watershed. The NWRC in cooperation with the Bureau of Land Management currently has plans to burn the watershed in the fall of 2005. Assuming a likely burn scenario and probable vegetation recovery, this study examines the potential changes in evapotranspiration, percolation and streamflow within the watershed in response to vegetation changes following a prescribed fire using the SHAW model.

Field Setting

The Upper Sheep Creek Watershed is a 26-ha snowfed rangeland watershed located within the Reynolds Creek Experimental Watershed in the Owyhee Mountains of southwest Idaho, U.S.A (43°N, 116°W). Annual precipitation is approximately 508 mm, approximately 60% of which falls as snow. Spring snowmelt is the primary source of runoff from the basin. Streamflow typically begins in March/April, peaks in May and ceases in July. Nearly all water reaching the stream is subsurface flow; overland flow is seldom observed in the basin.

The site has considerable spatial variability in soils, vegetation and snow cover. Low sagebrush areas are located predominantly on the windswept southwest-facing slopes and are bare of snow for much of the winter. Lower portions of northeast-facing slopes are dominated by mountain big sagebrush and typically accumulate about a meter of snow during the winter. Aspen thickets are established on the upper portions of the north-facing slopes where large snow drifts form annually. Soils vary from shallow (30 cm) and rocky under low sagebrush to deep (>2 m) silt loam under the aspen. The geology of Upper Sheep Creek consists of

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variably fractured and altered basalt underlain by dense basalt at a depth of 20 to 30 m (Winkelmaier 1987, Mock 1988, and Stevens 1991).

Previous Studies

A detailed study of the Upper Sheep Creek Watershed was conducted by the USDA-ARS Northwest Watershed Research Center from 1984 through 1994. Numerous investigations have been conducted to define the geology of the watershed (Winkelmaier 1987, Mock 1988, and Stevens 1991) and to better understand the processes controlling the hydrologic response of this mountainous watershed (Cooley 1988, Flerchinger et al. 1992, Flerchinger et al. 1993, Deng et al. 1994, Flerchinger et al. 1994, Neale et al. 1995, Tarboton et al. 1995, Unnikrishna et al. 1995, Flerchinger et al. 1996, Luce et al. 1998).

Flerchinger et al. (2000) computed a ten-year water balance of the Upper Sheep Creek Watershed. Because of its spatial heterogeneity, the watershed was broken into three zones based on similarity in soils, vegetation, and snow accumulation. The three zones are referred to as low sagebrush, mountain big sagebrush, and aspen, which comprise 58.9, 26.6 and 14.5% of the watershed, respectively. A partial water budget was computed for each of the three landscape zones. Average annual effective precipitation for the watershed was 471 mm over the ten-year period. Runoff from the watershed averaged 30 mm and was linearly correlated ($r^2 = 0.52$) to effective precipitation above a critical threshold of approximately 450 mm. Simulated percolation of the water beyond the root zone using the Simultaneous Heat and Water (SHAW) model correlated extremely well with measured runoff. A regression equation between simulated percolation and measured runoff can be written as ($r^2 = 0.94$; root mean square error = 7.1 mm):

$$R = -12.3 \text{ mm} + 0.565\, PERC \qquad (1)$$

where *R* and *PERC* are runoff and simulated percolation beyond the root zone, both in mm.

Post-Fire Regeneration

Vegetation studies during the ten-year study at Upper Sheep Creek determined that leaf area index (LAI) of the low sagebrush, mountain big sagebrush, and understory of the aspen site at the peak of the growing season is approximately 0.4, 1.2 and 1.0, respectively, based on point frame measurements. Leaf area index of the aspen canopy was 2.0. Vegetation characteristics used in the ten-year water balance simulation and assumed vegetation regeneration for a post-burn scenario are summarized in Table 1.

Table 1. Vegetation characteristics for unburned ten-year water balance and assumed vegetation regeneration for the first three years following a prescribed fire.

Landscape Area	Vegetation	Unburned		1st year		2nd Year		3rd year	
		LAI	Root depth (m)	LAI	Root depth (m)	LAI	Root depth (m)	LAI	Root depth (m)
Low Sagebrush	shrubs	0.4	1.0	0.4	1.0	0.4	1.0	0.4	1.0
Mountain Big Sagebrush	shrubs	0.72†	2.0	0.0	0.0	0.0	0.0	0.0	0.0
	grasses/forbs	0.48†	n/a	0.75	0.5	1.0	0.75	1.2	1.5
Aspen	aspen	2.0	2.0	0.2	2.0	0.4	2.0	0.6	2.0
	grasses	1.0	1.0	1.0	0.5	1.0	0.75	1.25	1.0

† Unburned analyses did not distinguished between LAI or rooting depth of shrubs versus grasses/forbs.

The low sagebrush zone (*Artemisia arbuscula*) has sparse vegetation with some grasses (*Poa secunda*) and considerable bare ground. Due to the lack of vegetation on this site, it is doubtful that it will carry a fire as is very typical of this ecosystem (USDA Forest Service 2003). Thus, post-fire conditions of the low sagebrush zone were assumed unchanged.

The mountain big sagebrush zone (*Artemisia tridentata vaseyana*) supports near complete cover of sagebrush, snowberry (*Symphoricarpos spp.*) and grasses. Pierson et al. (2001) compared burned and unburned areas at a site similar to Upper Sheep in northwestern Nevada. One year after the fire, grass and forbs replaced 35% of the total (shrub, grass and forbs) vegetation cover of burned coppice areas; percent cover of grasses and forbs within interspace areas recovered almost completely. This suggests a first-year post-burn LAI for Upper Sheep of approximately 0.75 consisting primarily of grasses and forbs. A first-year rooting depth of 0.5 m was assumed. Total LAI for the site was assumed to regenerate to pre-burn conditions within three years, consisting primarily of grasses with root depth extending down to a maximum depth of 1.5 m as suggested by Canadell et al. (1996) for bluebunch wheatgrass (*Agropyrun spicatum*). Mountain big sagebrush typically requires 15 years to recover (USDA Forest Service 2003), which is beyond the scope of this study and not considered a factor in short-term regeneration of the site.

The aspen zone consists of a thick stand of aspen (*Populus tremuloides*) and willow (*Salix spp.*) with an understory of mixed grasses. Although it can be difficult to initiate a crown fire in aspen, stands with abundant understory fuels can carry ground fires well under hot, dry fall conditions. Aspen have thin bark with little heat resistance and are easily top-killed by fire (USDA Forest Service 2003). Root systems of top-killed aspen send out suckers for several years after fire. Based on a typical ten-year recovery for aspen stands (USDA Forest Service 2003), the aspen was assumed to gain 0.2 LAI per year, with an unchanged pre-burn maximum root depth of 2 m. Grasses and forbs under the aspen were assumed to regenerate to their pre-burn levels within the first year.

Plant litter on the surface was assumed to be zero the first year following the study and gradually build to 2000 kg/ha of litter material with 40% ground cover by the third year for both the mountain big sagebrush and aspen zones. Pre-burn conditions are approximately 9000 kg/ha of litter material with about 90% ground cover resulting from ten years of exclusion from grazing.

Model Application

The original SHAW simulation for the ten-year water balance simulated 11 years (Sept 1983 through Sept 1994) to allow one year for the assumed initial conditions to equilibrate with climatic conditions. For this study, 11 separate simulations were conducted using the SHAW model, assuming a fire at the end of September for each respective year of the 11-year simulation. Vegetation regeneration scenarios presented in Table 1 were used in the model. Initiation of the growing season was adjusted each year based on snowcover depletion, but vegetation growth and regeneration were not adjusted for yearly weather variations. Changes in soil hydrophobicity and infiltration capacity were assumed not to limit infiltration of the low intensity snowmelt. Vegetation is secondary to the topographic influence on snow drifting in this watershed; given the unknown and complex effects of vegetation removal on drifting, the drift factors and effective precipitation determined by Flerchinger et al. (2000) were left unchanged for this study.

Results

Simulated annual evapotranspiration (ET) for the aspen and mountain big sagebrush zones are presented in Table 2 for the first three years following a fire. ET drops substantially the first year following the fire in response to vegetation removal. ET then increases each year, gradually returning to pre-burn conditions (within 2 mm) by the third year following a fire. Some third year ET estimates for the mountain big sagebrush are higher than pre-burn conditions due to higher soil moisture levels after two years of reduced ET (Table 2). This was not the case for the aspen because soil moisture deficits within the aspen zone are typically replenished with the spring melt season.

Simulated percolation for the mountain big sagebrush and aspen zones indicated relatively little response in percolation beyond the root zone for the first year following a fire, and percolation does not peak until the second year (Table 3). With a burn in the fall, spring runoff of the first post-fire year is influenced strongly by the moisture deficit created by pre-burn ET conditions. Thus, a response in percolation does not occur until the second post-fire snowmelt season. By then a reduced ET

Table 2. Comparison of annual evapotranspiration (mm) between unburned and 1st, 2nd, and 3rd year following a fire.

Year	Mountain big sagebrush zone				Aspen zone			
	No burn	1st Year	2nd Year	3rd Year	No burn	1st Year	2nd Year	3rd Year
1985	572	407	457	n/a	446	382	392	n/a
1986	582	377	425	529	491	391	436	469
1987	609	411	498	583	567	497	550	569
1988	409	312	364	471	516	435	496	510
1989	531	357	410	542	522	436	482	513
1990	491	381	435	529	526	491	500	523
1991	418	342	368	462	523	442	470	494
1992	307	267	292	349	511	433	496	509
1993	510	399	431	470	437	407	409	434
1994	491	303	361	449	500	430	475	494
Average	492	356	404	487	504	434	471	502
Percent †	100	72	82	99	100	86	93	100
p-value ‡	n/a	<0.001	<0.002	0.799	n/a	<0.001	0.001	0.035

† Percentage of annual ET compared to no burn
‡ Results of paired t-test comparing ET for respective post-burn years to ET with no burn

Table 3. Comparison of annual percolation beyond the root zone (mm) between unburned and 1st, 2nd, and 3rd year following a burn.

Year	Mountain big sagebrush zone				Aspen zone			
	No burn	1st Year	2nd Year	3rd Year	No burn	1st Year	2nd Year	3rd Year
1985	22	57	114	n/a	623	626	694	n/a
1986	32	84	191	156	815	833	894	864
1987	-30	-19	23	2	11	75	147	102
1988	-15	-15	1	-12	29	43	102	67
1989	-7	-2	28	61	612	616	688	642
1990	-6	-6	14	3	356	320	430	379
1991	-5	-5	-4	8	77	83	164	126
1992	-3	-3	-4	2	0	15	60	28
1993	52	65	89	110	754	725	808	769
1994	-12	-5	14	-6	143	137	202	180
Average	3	15	47	36	342	347	419	351
p-value †	n/a	0.052	0.019	0.032	n/a	0.558	<0.001	<0.001

† Results of paired t-test comparing percolation for respective post-burn years to percolation with no burn.

Table 4. Comparison of runoff (mm) between unburned and 1st, 2nd, and 3rd year following a burn.

Year	No burn	1st Year	2nd Year	3rd Year	Unburned Upper Bound 90% C.I.
1985	85	91	98	n/a	99
1986	93	102	123	111	108
1987	0	0	2	0	3
1988	0	0	0	0	7
1989	37	38	48	49	47
1990	16	13	25	19	29
1991	0	0	0	0	12
1992	0	0	0	0	7
1993	67	67	77	77	78
1994	0	0	7	2	15
Average	30	31	38	34 ‡	
p-value †		0.314	0.017	0.039	

† Results of paired t-test comparing runoff for respective post-burn years to percolation with no burn; t-test considered only those years where runoff occurred.
‡ 3rd year average computed using 85 mm of runoff for 1985.

season results in lower soil moisture deficits and increased subsurface flow.

Areal percolation (Table 3) translates directly to estimated runoff (Table 4) using the relationship established in Equation (1). Interestingly, a pairwise t-test comparing the first year runoff with unburned runoff shows no significant difference. Runoff is greatest the second year following the fire and somewhat less the 3rd year in this basin dominated by subsurface flow. A year of reduced ET is necessary following the fire to decrease the soil moisture deficit and significantly influence percolation through the root zone, subsurface flow and, ultimately, runoff from the basin.

Comparison of the upper bound of the 90% confidence interval in runoff for no burning in Table 3 with estimated runoff following a fire indicates that for years with measured runoff, the second year is generally near the upper bound of the 90% confidence interval. Therefore, a year with adequate runoff will be necessary to detect a response in runoff after a fire. The ten-year water balance study occurred during a period of below normal precipitation; long-term average precipitation for the watershed is around 508 mm compared to 471 mm for the ten-year study. Of the 18 years of runoff records from Upper Sheep, five of the six years with no runoff were within this ten-year period. Consequently, there is a greater likelihood of detecting an increase in runoff in response to a fire than the ten-year study might indicate.

Summary and Conclusions

Simulated ET was significantly less the first year following a fire compared to that for no burning as a result of vegetation removal, but gradually returned to pre-burn conditions by the third year following a fire. After a year of significantly less ET, percolation was significantly greater during the second post-fire year (Table 3). Increases in percolation during the first year following the fire were marginally significant compared to pre-burn conditions for the mountain big sagebrush zone but were not significantly different in the aspen zone. Percolation during the first spring snowmelt season was influenced by soil moisture deficits created by pre-burn vegetation conditions. A significant response in percolation to a fire was not observed until after a year of reduced ET and soil moisture deficit.

The delayed response in percolation translated directly into a delayed runoff response in this system dominated by subsurface flow. Runoff was not significantly changed during the first year following a fire. This observation may be specific to this and similar watersheds dominated by subsurface flow and is unlike watersheds dominated by overland flow and surface runoff where flows are more likely to increase during the first year following a fire.

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