Fire Severity and Watershed Resource Responses in the Southwest

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A conceptual model outlining the effect of different fire severities on postfire hydrologic responses has been presented earlier (DeBano et al 1995). This conceptual model portrays fire severity as a continuum, ranging from minor resource responses under a cool-burning prescribed fire to the major responses that could be expected to occur during stand-replacing wildfires in forests. The fire response continuum in the southwestern United States is large (Baker 1990). In this model, prescribed fire conditions represent lower temperature–higher humidity burning conditions where fuel loading is minimal and fuel moisture is high. These conditions produce lower fire intensities and thus expose the soil and water resource to lower fire severities. Prescribed fire usually has minor hydrologic impacts on watersheds because the surface vegetation, litter, and forest floor are only partially burned (Baker 1990). Other resources (soils, wildlife, etc.) are also changed little by a prescribed fire. On the other end of the fire response continuum, fire behavior more nearly represents that present during wildfires, where the temperatures, wind speeds, and fuel loadings are high and the humidities and fuel moistures are low. In contrast to prescribed burning, wildfires can have a major effect on basic hydrologic processes, leading to increased sensitivity of the site to erosion and to reduced land stability (Baker 1990). Large changes also occur in other resources, including denuded landscapes, large losses of plant nutrients, and so forth.

The differences in impacts between prescribed burning and wildfires depend partly on the vegetation type being burned. For example, there can be large differences in ponderosa pine forests; during a cool prescribed fire, only the litter and smaller diameter surface fuels are ignited, as compared to near total canopy consumption during intense wildfire. In contrast, fires burning in chaparral are mainly carried by the shrub canopies. Therefore, it is more difficult to control the behavior and intensity of chaparral fires so that only minimum impacts to the soil and vegetation occur. To obtain less severe fires in chaparral, fires are ignited during marginal burning conditions, or by using special heat-generating ignition techniques (e.g. Helitorch, etc.). Also, low-severity fires in chaparral often result in mosaics of burned and unburned patches, because the slight differences in slope and aspect make total ignition and coverage impractical. Although some sites in the mosaic pattern are burned severely, a lower average fire severity results for the entire area.

Before the conceptual model described above can be developed, response functions for the different resources to a range of fire severities need to be better quantified. Other important factors affecting the postfire hydrologic scenario are postfire precipitation patterns and slope. The hydrologic response model is generally visualized as a three-dimensional surface with a particular hydrologic response (peak flow, sedimentation rate, etc.) being a function of both fire severity and a time variable reflecting climatic events following a fire. Individual differences in site parameters unique to a given area (e.g. slope, aspect, soils, etc.) would also have to be considered. The immediate soil and watershed response (how much litter and plant cover had been destroyed by the fire, amount of nitrogen volatilized, etc.) would be most closely related to fire severity, and would probably be a non-linear function such as the one that describes infiltration into a wettable dry soil. An additional time function, reflecting precipitation events, would be necessary to define the longer term hydrologic responses to a particular fire severity. The dimension of time is essential for the model because of the possibility of variable precipitation events that could follow a fire. For example, a low-intensity prescribed fire can produce substantial runoff and soil loss as sediment if

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the fire is immediately followed by high-intensity rainstorm events. Conversely, severely burned watersheds can produce little runoff and erosion if a fire is followed by a relatively mild year with gentle rains and warm temperatures that allow a protective vegetation cover to develop. The pattern of precipitation events over time is stochastic in nature, and would have to be viewed in a probability framework so that relevant outcomes could be explored. The effects of "big" storms in the Southwest are of particular importance. It may be that low-probability, high-impact events are more important in prescribed burning decision criteria than long-term average outcomes, reflected in the expected values of probability distributions. Information for the two-dimensional part of this model has been developed by Ffolliott et al. (1988), and with some modification could be used as a starting point for developing the time dimension following fire.

The first iteration of the above model is being developed to describe select watershed responses. All available information on hydrologic responses for the southwestern United States is currently being consolidated to define and quantify hydrologic responses to wildfires and, more importantly, to cooler burning prescribed fires. Unfortunately, only a meager data base is available on the hydrologic responses of watersheds burned at lower severities. The best data set available was collected during a case study of the Rattle Burn in north-central Arizona (Campbell et al. 1977), and it was used to quantify the conceptual model described above for ponderosa pine forests. Additional information is also presented on other vegetation types, but it only reflects differences between wildfires and prescribed burns and not intermediate fire severities.

Ponderosa Pine Example

A wildfire designated as the Rattle Burn (May 7–9, 1972) swept through 290 ha of even-aged stands of ponderosa pine growing on sedimentary-derived soils on the West Fork of Oak Creek of the Coconino National Forest, at an elevation of 2,040 m about 29 km southwest of Flagstaff. Three small watersheds, representing severe and moderate burns and an unburned control, were established to assess the effects of wildfire on hydrology, soils, timber and forage production, and wildlife populations. On the moderately burned watershed, fire was generally confined to the forest floor. The intensity on the moderately burned site was calculated to be 9,000 kjoules/sec/m. Most of the trees were killed on the severely burned watershed. The fire intensity on the severely burned watershed was calculated to be 35,000 kjoules/sec/m. A nearby unburned watershed served as a control.

Streamflow was measured with automatic stream stage recorders at the outflow points of each watershed between 1973 and 1975. The mean annual water yields were 0.5 cm from the unburned watershed, and 2.0 and 2.8 cm from the moderately and severely burned watersheds, respectively. Although the differences in annual water yield were small between the watersheds, the differences in peak flows were much larger. The highest annual peak discharge on the control watershed was only 0.01 $m^3/s/km^2$. On the moderately burned watershed, peak discharge reached 0.24 $m^3/s/km^2$, while on the severely burned watershed the peak discharge exceeded 4.067 $m^3/s/km^2$. The number of runoff events during the period 1972–75 also increased with severity of burning, ranging from 6, 15, and 25 for the unburned, moderate, and severe burns, respectively. The increased peak runoff was also reflected in suspended sediment yields. The total suspended sediment yield for 1972–75 was 3, 20, and 1559 kg/ha for the unburned, moderate, and severe burns, respectively. The suspended sediment losses occurred during the first two years, and particularly during the second year when all-time precipitation records were set.

The suspended sediment data from the Rattle Burn were used to establish maximum responses that might be expected over time from a ponderosa pine forest that had been subjected to different burning severities in situations similar to those on the Rattle Burn. Best estimates of the duration of sediment production response were combined with the maximum numbers to generate a response relationship for a particular severity (Figure 1). It is assumed, in general, that annual sediment production increases on watersheds burned at moderate severity will be less in magnitude and much shorter in duration than those that were severely burned. Probably after a couple of growing seasons, little response will be evident on the moderately burned watersheds. In contrast, the response curves for watersheds receiving severe burns will be greater in magnitude and longer in duration than for the moderately burned watersheds, perhaps lasting up to 15 years. These time periods are consistent with other resource responses (Ffolliott et al. 1988). Although no information was available on the low-severity fire, it was assumed that there would be no substantial

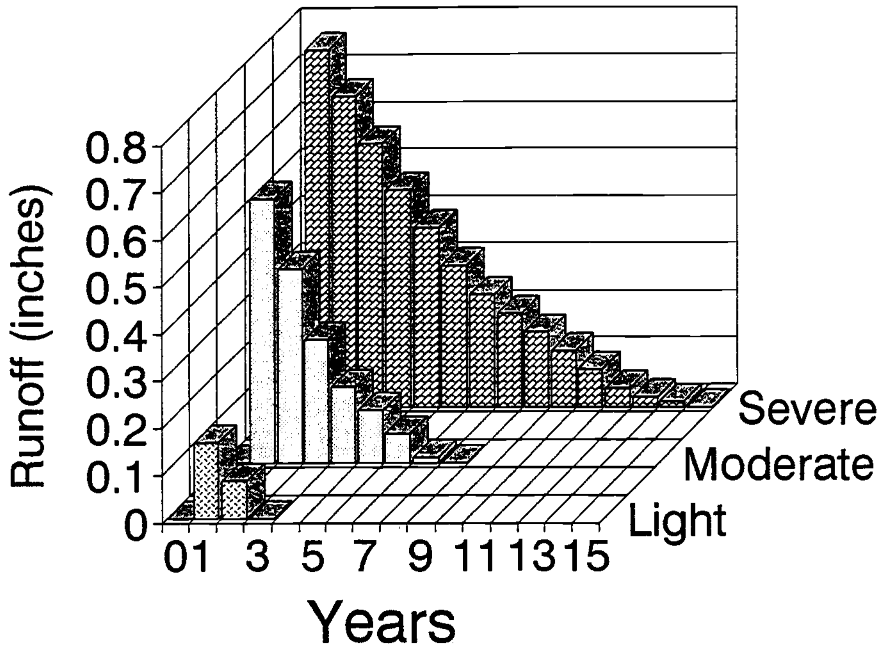

Figure 1. Average increases in annual sediment yield over time from ponderosa pine watersheds that were severely, moderately, and lightly burned.

increases in streamflow or sediment production. Data from ponderosa pine stands in California confirm that no significant increases in sediment losses can be expected following a low-intensity prescribed burn (Biswell and Schultz 1965).

Chaparral and Other Southwestern Vegetation Types

Data showing the hydrologic response to fire for chaparral and other vegetation types in the Southwest are limited to several case studies reporting on wildfires and some prescribed burns. There are only a few published reports on watershed responses to prescribed burning. Unfortunately, data do not exist for many vegetative types on intermediate fire severities, nor are there studies on paired watersheds such as were available for the ponderosa pine example discussed above. Also, the differences in prescribed burn severities between wildfires and prescribed burns in chaparral are usually not as great as for ponderosa pine forests, because chaparral fires are carried mainly by the brush canopies and consequently the severities are high in those areas where the canopy is consumed. As indicated above, the overall severity for a watershed may be mitigated by burning in a mosaic pattern where the entire area is not burned.

Fire increases sediment loss in all vegetation types in the Southwest, as well as in the ponderosa pine forests discussed earlier. Table 1 shows substantial differences in sediment losses from wildfires compared to prescribed burning in both Arizona and California chaparral. In California chaparral, for example, sediment losses after wildfires amounted to 55.3 Mg/ha following wildfires, compared to losses of 5.5 Mg/ha from similar unburned sites (Krammes 1960). After wildfires in Arizona chaparral, sediment losses up to 204 Mg/ha have been reported (Glendening et al. 1961). The available data indicate that sediment losses following prescribed burns in chaparral are much lower than for wildfires. For example, a study by Pase and Lindenmuth (1971) in central Arizona showed sediment losses of only 3.8 Mg/ha after a prescribed burn. Likewise, sediment yields from the Battle Flat watersheds following a mosaic burn amounted to about 0.03 Mg/ha compared to only a trace of erosion (less than .001 Mg/ha) from a nearby watershed (Overby and Baker 1995). In general, the sediment losses following chaparral fires (both wild and prescribed) usually exceeded those reported for ponderosa pine forests (Table 1).

Slope also has an important effect on the sediment losses following both prescribed burns and wildfires, and needs to be considered when using the conceptual model described above. Some information is available on the effect of fire on

Table 1. Sediment losses the first year after prescribed burns and wildfires in the Southwest.

Location	Watershed Condition		Sediment Loss First Year (Mg/ha)	References
California	Ponderosa pine	Control	<0.001	Biswell and Schultz 1965
		Prescribed Fire	<0.001	
California	Chaparral	Control	0.043	Wright et al. 1976
		Wildfire	28.605	
California	Chaparral	Control	5.530	Krammes 1960
		Wildfire	55.300	
Arizona	Chaparral	Control	0.000	Pase and Lindenmuth 1971
		Prescribed Fire	3.778	
Arizona	Chaparral	Control	0.175	Glendening et al. 1961
		Wildfire	204.000	
Arizona	Ponderosa pine	Control	0.003	Campbell et al. 1977
		Wildfire	1.254	
Arizona	Mixed conifer	Control	<0.001	Hendricks and Johnson 1944
		Wildfire, 43% slope	71.680	
		Wildfire, 66% slope	201.600	
		Wildfire, 78% slope	369.600	
Texas	Juniper\grass	Control, level	0.025	Wright et al. 1982
		Burned, level	0.029	
		Control, mod. slope	0.076	
		Burned, mod. slope (15–20%)	1.874	
		Control, steep slope	0.013	
		Burned, steep slope (43–54%)	8.443	

different slopes in pinyon-juniper woodlands and mixed conifer forests. In mixed conifer forests in central Arizona, sediment losses the first year following a wildfire were 0.001 Mg/ha on level topography compared to up to 370 Mg/ha on a 78 percent slope (Hendricks and Johnson 1944, Table 1). Intermediate amounts of 72 and 202 Mg/ha occurred on 43 and 66 percent slopes, respectively. Similar effects of slope on sediment losses have been reported for juniper/grass-covered watersheds in Texas (Wright et al. 1982). Sediment losses increased nearly 650 fold on slopes of 43–54 percent compared to trace amounts on level ground. Increases of about 25 fold were reported on slopes of 15–20 percent.

Conclusions

Fire occurs frequently in southwestern ecosystems in the form of either wildfires or managed prescribed burns. Managers are often asked to assess the effects of fire on the soil and water resources. It is important during these evaluations to clearly distinguish between wildfires and prescribed fires, and the severities associated with each. A conceptual model outlining the different responses is presented in this paper. The model portrays fire severity as a continuum, with responses ranging from minor resource responses under a cool-burning prescribed fire to major responses which could be expected to occur during stand-replacing wildfires in forests; the fire response continuum in the southwestern United States is large (Baker 1990). In this model, prescribed fire conditions represent lower temperature–higher humidity burning conditions where fuel loading is minimal and fuel moisture is high. These cooler burning conditions produce lower fire intensities, and thus expose the soil and water resource to lower fire severities.

Postfire precipitation regimes and slope are also important factors when evaluating hydrologic responses to fire. The effects of "big" storms in the Southwest are of particular importance. Big storms on gentle slopes that have burned less severely could yield large amounts of sediment. Conversely, even severely burned steep slopes may not contribute substantial amounts of sediment if only low-intensity storms occur after the fire until vegetation becomes established. It may be that low-probability, high-impact events are more important in prescribed burning decision criteria than long-term average outcomes, reflected in the expected values of probability distributions. These postfire responses to a given precipitation regime will also depend on the slope of the burned area. Sediment production generally increases exponentially with slope and this increase can be magnified by fire.

Although the conceptual model of a fire continuum is useful for describing general soil and watershed responses, more quantitative data are needed before it can be used to assess the magnitude of response. Some information is available in the literature for most vegetation types in the Southwest. However, these data are generally limited to the effect of wildfire on hydrologic responses. Only a few studies have reported hydrologic responses as they are related to fire severity. The best data available are for ponderosa pine forests in central Arizona, and this data set is limited to one case study.

Although the conceptual model cannot be fully implemented with existing data sets, an evaluation of the existing information clearly shows that low-severity prescribed fires in all vegetation types produce much smaller hydrologic responses (e.g. runoff, sediment losses) than are experienced during wildfires. In many cases, more than a hundred-fold increase in response has been reported for wildfires compared to prescribed burns. Because there are large differences in watershed responses between wildfires and prescribed burns, it is necessary to clearly differentiate between the two when assessing fire effects. For example, it is not of much value to use published information on wildfire effects when trying to predict the hydrologic responses of a planned prescribed burn due to the differences in fire severities and associated hydrologic responses. Generally, fire increases sediment losses, but this impact may be tempered by postfire precipitation regimes and slope.

Literature Cited

Baker, M.B., Jr. 1990. Hydrologic and water quality effects of fire. Pages 31–42 in J.S. Krammes, technical coordinator. Effects of fire management of southwestern natural resources, workshop proceedings. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station General Technical Report RM-191. Fort Collins, CO.

Biswell, H.H. and A.M. Schultz. 1965. Surface runoff and erosion as related to prescribed burning. J. For. 55:372–373.

Campbell, R.E., M.B. Baker, Jr. and P.F. Ffolliott. 1977. Wildfire effects on a ponderosa pine ecosystem: An Arizona case study. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Research Paper RM-191. Fort Collins, CO. 12 pp.

DeBano, L.F., M.B. Baker, Jr. and P.F. Ffolliott. 1995. Effects of prescribed fire on watershed resources: A conceptual model. Hydrology and Water Resources in Arizona and the Southwest 22–25:39–43.

Glendening, G.E., C.P. Pase and P. Ingebo. 1961. Preliminary hydrologic effects of wildfire in chaparral. Modern techniques in water management. Proceedings of the 5th Annual Arizona Watershed Symposium. 4 pp.

Ffolliott, P.F., D.P. Guertin and W.D. Rasmussen. 1988. Simulating the impacts of fire: A computer program. Environmental Management 12:809–814.

Hendricks, B.A. and J.M. Johnson. 1944. Effects of fire on steep mountain slopes in central Arizona. Journal of Forestry 42:568–571.

Krammes, J.S. 1960. Erosion from mountain side slopes after fire in southern California. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Research Note PSW-171. Berkeley, CA. 9 pp.

Overby, S. and M.B. Baker, Jr. 1995. Sediment and nutrient regime from a central Arizona chaparral watershed. Hydrology and Water Resources in Arizona and the Southwest 22–25:63–67.

Pase, C.P. and A.W. Lindenmuth, Jr. 1971. Effects of prescribed fire on vegetation and sediment in oak-mountain mahogany chaparral. J. For. 69:800–805.

Wright, H.A., F.M. Churchill and W.C. Stevens. 1976. Effect of prescribed burning on sediment, water yield, and water quality from dozed juniper lands in central Texas. J. Range Manage. 29:294–298.

Wright, H.A., F.M. Churchill and W.C. Stevens. 1982. Soil loss and runoff on seeded vs. non-seeded watersheds following prescribed burning. J. Range Manage. 35:382–385