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WILDFIRE IMPACTS ON RESERVOIR SEDIMENTATION IN THE WESTERN UNITED STATES

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Abstract: Wildfires change the soil properties and hydrologic conditions of watersheds upstream from reservoirs. If a wildfire is soon followed by high-intensity rainfall, then runoff and erosion can increase to a degree that depends upon the tectonic and geologic characteristics of the burned watershed. We develop a wildfire impact index covering a large scale (10^6 km^2) to identify reservoirs expected to experience post-fire sedimentation. Reservoirs in the western United States that are most likely to be affected by wildfire are in the mountains of the southwest and along the tectonically active west coast.

Keywords: Sedimentation, Reservoirs, Wildfire, Sediment yield, Runoff, Erosion, GIS

1 INTRODUCTION

Reservoirs have been constructed in diverse geologic terranes, which reflect both underlying rock type and tectonic status. In the western United States 32,723 dams have been constructed since 1819 in the 17 conterminous states west of the line running from North Dakota to Texas (U.S. Army Corps of Engineers, 2004). Many of these are in steep topography in watersheds draining forest or grassland ecosystems. As such, the reservoirs are susceptible to the erosional and depositional consequences of wildland fires that burn within their watersheds. For example, in California it has been well documented that reservoirs or debris flow basins are affected by the near-certain flood and erosion response of burned watersheds (Anderson, 1949, 1976; Rowe *et al*., 1954; Staff of the San Dimas Experimental Forest, 1954). In general, impacts from post-fire runoff are a result of the changes in the hydrologic conditions and soil properties of burned watersheds. These changes include: (1) the loss of overstory canopy and litter and duff on the forest floor, (2) the increase in water repellency as a result of chemical and physical changes in the soil (DeBano, 2000), (3) the decrease in the critical shear stress for soil erosion (Moody *et al*., 2004), (4) surface sealing by ash (Mallik *et al.*, 1984) and soil particles (Neary *et al*., 1999), and (5) the loss of surface obstructions, which alters hillslope friction and the time-to-concentration resulting in greater peak discharge.

In this paper we develop a wildfire impact index that indentifies the potential for wildfire impacts on reservoir sedimentation in a variety of geologic terranes within a study area. This study area consists of a portion of the western United States, including parts of the 17 states west of the Mississippi River, a total area of about 3 × 10^6 km^2 (Fig. 1). Using ecoregions defined by Bailey (1995), we limited the study area to exclude those ecoregions commonly designated as tall grass and short grass prairie. These ecoregions generally occupy rolling or level sites where post-fire erosion is minimal owing to the protection of the soil surface by basal crowns, fibrous and extensive root systems, ash, charcoal, and unconsumed litter (Daubenmire, 1968; Vogl, 1974). The reservoirs we considered are in the National Inventory of Dams (NID) maintained and published by the U.S. Army Corps of Engineers (2004). Using the wildfire impact index, we identify some of the reservoirs that may be impacted by wildfire. We then present quantitative sediment yields from the few published investigations that relate reservoir sedimentation to wildfires. Thus, we provide some verification of the wildfire impact index.

2 METHODS

The wildfire impact index, *W*, was based on physical principles of sediment transport. Four variables were input into data layers with 1-km^2 resolution for GIS (Geographical Information System) analysis: fire-return interval or fire frequency (Schmidt *et al*., 2002), soil erodibility (Wolock, 1997), channel slope (U.S. Geological Survey, 2004), and the 30-min maximum rainfall intensity (Hershfield, 1961). Fire frequency, *F*, was used instead of fire severity because we have evidence from the Cerro Grande Fire in New Mexico (Moody and Martin, unpublished data) that runoff and therefore erosion is independent of fire severity in vegetation types like ponderosa pine where litter and duff are important components of the hydrologic response. The soil-erodibility factor, *K* (m^{-1}), has been mapped over much of the western United States (Renard *et al*., 1997). Its use has some problems for quantitative prediction and generalization, which have been discussed by Moody *et al*., 2004, but it suffices as a relative measure of erodibility. Channel slope partially determines sediment transport, q_s (kg·s^{-1}), which depends on the boundary shear stress, τ (N·m^{-2}) such that $q_s \propto \tau^c$, where *c* ranges from 1.0 - 4.5 (Wilcock, 1997). The total boundary shear stress is

$$\tau = \rho g h S \tag{1}$$

where ρ (kg ·m^{-3}) is the density of water, g (m·s^{-2}) is the acceleration of gravity, *h* (*m*) is the water depth, and S is the channel slope. By using a Manning's n type resistance equation the depth is

$$h = (\frac{nq}{S^{0.5}})^{0.6} \tag{2}$$

where q (m^2·s^{-1}) is the unit discharge. Thus, assuming *c*=1.5 (Meyer-Peter and Müller, 1948), and substituting Eq. (2) into (1) gives the sediment transport as

$$q_s - \tau^c = q^{0.9} S^{1.0} \tag{3}$$

The 30-min maximum rainfall intensity, I_{30} (mm·h^{-1}) determines the peak discharge from burned watersheds and the relation is an empirical power-law equation of the form

$$q_{peak} = a I_{30}^{b} \tag{4}$$

where *a* is the proportionality coefficient, and *b* averaged 3.0 for rainfall greater than about 10 mm h^{-1} in three burned watersheds in South Dakota, Colorado, and New Mexico (Moody and Martin, 2001a). Substituting Eq. (4) into Eq. (3), multiplying by the fire frequency and soil-erodibility factor, and normalizing by the maximum value of each variable, *F*, *I*, *S*, and *K* for the study area, yields the wildfire impact index:

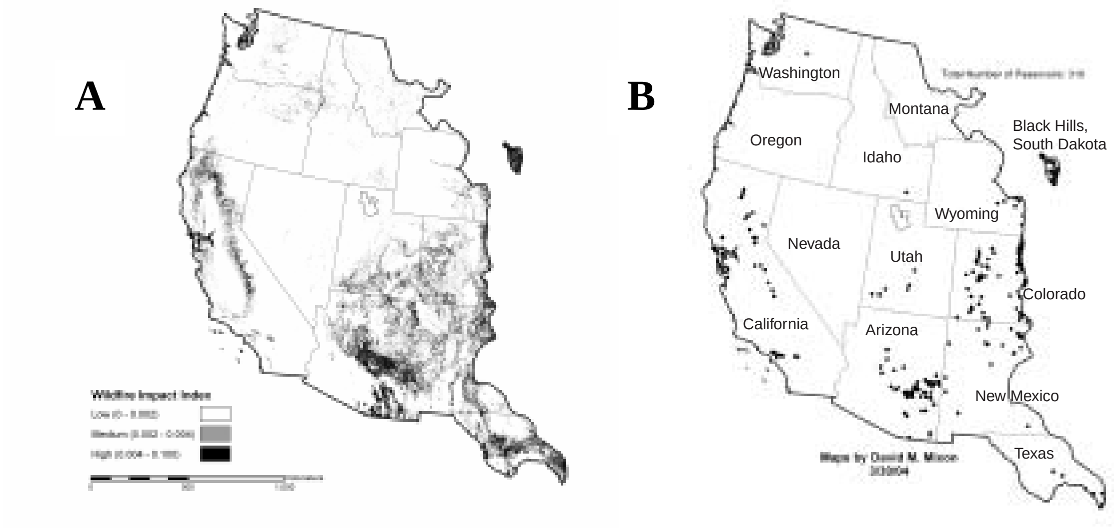
$$W = \left(\frac{F}{F^{\max}}\right)\left(\frac{I_{30}}{I_{30}^{\max}}\right)^{3.0}\left(\frac{S}{S^{\max}}\right)^{1.0}\left(\frac{K}{K^{\max}}\right) \tag{5}$$

Values of the index, *W*, were grouped into low, medium, and high categories using a "standard deviation" classification scheme. This index has a similar form to multiplicative empirical relations developed by Anderson (1949) and Loomis *et al*. (2003).

3 RESULTS

The wildfire impact index for the mountainous western United States is highest in the southwestern states of Arizona, Utah, Colorado and New Mexico. Other areas in the high category are the Sierra Nevada along the eastern side of California, the Transverse Ranges in southern California, the east-facing side of the Cascades in Washington, and the Black Hills in South Dakota (Fig. 1A). The basin and range mountains of Nevada and the mountain ranges along the border of Idaho and Montana are in the medium and low categories of the wildfire impact index.

The National Inventory of Dams lists 8,106 dams of various sizes within the study area. The density of dams is highest in the Rocky Mountains of Colorado, the Sierra Nevada, the Transverse and Coast Ranges in California, and the Cascades of Oregon and Washington. From this set of dams, there were 319 dams that were within the 1 km^2 grid cells having the high-impact attribute (Fig. 1B). Most of these dams were in Arizona, California, and Colorado, and none were in Montana or Nevada.



A. Wildfire Impact Index that Includes Effects of Fire Frequency, Soil Erodibility, Channel Slope, And 30-Minute Maximum Rainfall Intensity. **B**. Location of Only those Reservoirs Within the Black areas in Fig. 1A Where the Wildfire Impact Index is High. Reservoirs Just Outside and Downstream from Some areas With a High Wildfire Impact Index are not Shown.

Fig. 1 Location of the Study Area.

4 DISCUSSION

The wildfire impact index had different sensitivities to each of the variables. For example, fires are more frequent in ponderosa-pine ecosystems than in the higher elevation mixed-conifer ecosystems (Agee, 1993). The effect of channel slope shows clearly in Fig. 1A in the density of wildfire impacts in the mountain ranges in Arizona, Utah, Colorado, and New Mexico, and in the Sierra Nevada and Transverse Ranges in California. The effect of the rainfall intensity is to increase the index in the mountain ranges in the southwest where convective storms with high rainfall intensity (Hershfield, 1961) are associated with the flow of moist summer monsoon air from the Gulf of California. This monsoon effect diminishes northward across Utah, Colorado, and New Mexico; however, Colorado and New Mexico are affected, at times, by a second source of moist air from the Gulf of Mexico. The index is low in the northwestern part of the western United States where convective storms are less common and intense rain frequently falls on moist soils rather than dry soils as is common in the southwestern United States (Wondzell and King, 2003). Moreover, this area is far from the source of monsoon air and is dominated by a maritime rainfall regime, which is characterized by long duration, low-intensity rain or rain-on-snow events. The soil-erodibility factor, K, had a spatially-variable distribution over small scales (1,000 km^2) similar to slope and did not produce any regional scale trends (1,000,000 km^2) similar to those shown by the rainfall intensity factor. The wildfire impact index is a relative estimator of sediment transport. It does not provide quantitative predictions of sediment-transport rates, but rather indicates regions where wildfire may have a greater impact on reservoir sedimentation relative to other regions.

Dams in the areas of high wildfire impact are located in several different geologic terranes. Those in Colorado and New Mexico are in a tectonically stable region: folded consolidated rocks underlie the eastern edge of the study area; unconsolidated deposits, intrusive igneous, metamorphic and volcanic rocks underlie the central part; flat-lying to gently-dipping, consolidated and semiconsolidated rocks underlie western Colorado and Utah (Heath, 1988). Dams in Arizona also are in a tectonically stable region, in which primarily volcanic rocks and intrusive igneous and metamorphic rocks form part of a basin and range topography. Dams in California are in both a tectonically stable zone (intrusive igneous and metamorphic rocks of the Sierra Nevada) and in a tectonically active zone along the western edge of California, which includes the Transverse Ranges in southern California and the Coast Ranges along the central California coast. It is important to remember that the 319 dams represented in Fig. 1B are those that are within a 1-km^2 grid cell associated with a high wildfire impact attribute. Some dams are not represented in Fig. 1B because they are downstream from and not co-located within the high-impact area, yet the associated reservoir may have a high potential impact from wildfire. Thus, the number of reservoirs affected by wildfire is larger than 319.

Previous field investigations of post-fire reservoir sedimentation provide verification of the wildfire impact index in some geologic terranes. Investigations are lacking in the areas identified as having a low wildfire impact index, and most investigations are in areas identified as having a high wildfire impact index. For example, one of our investigations was in a high impact area in the tectonically stable Rocky Mountain region along the eastern edge of the study area. The 1996 Buffalo Creek Fire burned approximately 50 km^2 upstream from the Strontia Springs Reservoir, which provides water to the cities of Denver and Aurora. The estimated average annual pre-fire, total-load transport rate was about 48,000 $m^3 \cdot yr^{-1}$and the annual bed-load rate was about 16,000 $m^3 \cdot yr^{-1}$ from the South Platte River drainage area of about 7,800 km^2 (Borland, 1978). A major flood following the wildfire transported about twice the annual bed-load (31,000 m^3) into the reservoir and about three times (154,000 m^3) the annual total-load in about 2 days. We are uncertain of the actual area that contributed sediment from the burned watersheds upstream and, therefore, we have not reported sediment yields as mass per unit area per unit time (Moody and Martin, 2001b, c). However, many previous sedimentation investigations have made this assumption of spatially-uniform erosion per year. Therefore, for the sake of comparison in this paper, we have extrapolated our sediment transport results in both space and time and computed sediment (total-load and bed-load) yields in $kg \cdot ha^{-1} \cdot yr^{-1}$(Table 1).

The increase in post-fire sediment yield deposited in Strontia Springs Reservoir in a tectonically stable terrane was greater than the increased yield from some other geologic terranes after wildfires. The increase can be measured by the erosion ratio (post-fire annual sediment yield/pre-fire annual sediment yield). In the tectonically active Transverse Ranges of southern California, Eaton (1936) and Troxell and Peterson (1937) published similar post-fire sediment yields (Table 1). These yields are similar to those predicted by Anderson (1949), who also predicted an erosion ratio (11) for the first year after a wildfire. Rowe *et al.* (1954) predicted a comparable ratio (35). The sediment yields from watersheds burned by the Buffalo Creek Fire are less than those from the Transverse Ranges but the erosion ratio (560) is greater. A similar large erosion ratio (2,900) was calculated for data published by Glendening *et al.* (1961) for the first year after the 1959 Boulder Mt. Fire near the Roosevelt Reservoir in Arizona and a moderately large ratio (150) was reported by Lavine *et al.* (2001) for the first year after the 2000 Cerro Grande Fire upstream from the Los Alamos reservoir (Table 1). These large erosion ratios arise because the annual yield is assumed to be uniform over the

Table 1 Comparison of Sediment Yields in Different Geologic Terranes affected by Wildfire

[Based on sediment trapped behind dams of various sizes; a bulk density of 1700 kg m^{-3} was used in converting volume to mass unless noted otherwise; erosion ratio = post-fire annual sediment yield / pre-fire annual sediment yield]

Reference	Years after fire (yr)	Total-load Extrapolated Yields (kg $\cdot ha^{-1} \cdot yr^{-1}$)	Bed-load Extrapolated Yields (kg $\cdot ha^{-1} \cdot yr^{-1}$)	Erosion ratio
Colorado--Tectonically stable; Pikes Peak granitic bedrock				
Moody and Martin, 2001c	pre-fire	100	35	--
	1	0.056×10^6	0.006×10^6	560
	2	--	240	--
California--Tectonically active; Transverse Ranges, igneous and metamorphic bedrock				
Eaton, 1936	1	0.40×10^6	--	--
Troxell and Peterson, 1937	1	0.22×10^6	--	--
Anderson, 1949	pre-fire	0.049×10^6	--	--
	1	0.56×10^6	--	11
Rowe et al., 1954	pre-fire	-0.01×10^6	--	--
	1	0.38×10^6	--	35
	2	-0.12×10^6	--	12
Doehring, 1968	1	0.077×10^6	--	--
Rice, 1973	1	0.75×10^6	--	--
California--Tectonically active; Coast Range; folded consolidated bedrock				
Booker et al., 1993	1	4,700	--	--
Ritter and Brown, 1972	pre-fire	0.006×10^6		--
	1	0.043×10^6		7
Arizona--Tectonically stable; granitic bedrock				
Glendening et al., 1961	pre-fire	340	--	--
	1	0.99×10^6	--	2,900
	2	0.10×10^6	--	290
New Mexico--Tectonically stable; volcanic bedrocks				
Lavine et al., 2001[a]	pre-fire	67	--	--
Malmon et al., 2002[a]	1	0.016×10^6	0.004×10^6	150
Washington--Tectonically active; East slope of Cascades; volcanic and intrusive bedrock				
Helvey, 1980	pre-fire	14	--	--
	1	261	--	19

[a] A bulk density of 1,000 kg m^{-3} was used for the volcanic sediment

entire drainage area. However, we know that yields after the Buffalo Creek Fire were derived almost exclusively from two smaller sub-watersheds (-50 km^2) within the large South Platte River watershed (-7,800 km^2) and certainly from even smaller areas adjacent to the channel network in each sub-watershed (Moody and Martin, 2001b, c). This illustrates the localization of sediment erosion and the problem with reporting erosion as uniform yields; therefore erosion ratios should be used for general comparisons only.

5 CONCLUSIONS

The wildfire impact index indicates relatively high impacts on reservoirs in three major geologic terranes: (1) tectonically stable mountains of the southwestern United States (Arizona, Utah, Colorado, and New Mexico), (2) tectonically active Transverse and Coast Ranges in California, and (3) tectonically stable Sierra Nevada in eastern California. Given that we identified reservoirs with a high wild fire impact index in several different geologic terranes, we think that the four variables (fire frequency, soil erodibility, channel slope, and rainfall intensity) are more important than the type of geologic terrane in determining post-fire sedimentation.

Predictions of the potential impact of wildfire on reservoirs in the western United States have been based on present conditions. Wildfire throughout the western United States may be expected to increase because of increased fuel loading from fire suppression (Brown *et al.*, 2004) and from increasing population pressure from surrounding areas. Moreover, potential climate change may combine with fuel loadings and future population pressure to change the present conditions and alter the relative magnitudes of the wildfire impact index. This predictive technique is applicable to other parts of the world where land-use changes may simulate climate change and population pressures continue to increase the risk of wildfires and their impact on reservoir sedimentation.

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