LONG-TERM HYDROLOGIC RESEARCH ON THE SAN DIMAS EXPERIMENTAL FOREST, SOUTHERN CALIFORNIA: LESSONS LEARNED AND FUTURE DIRECTIONS

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Abstract—The San Dimas Experimental Forest (SDEF) is located in the San Gabriel Mountains, about 45 km northeast of Los Angeles, California. The SDEF was originally established in 1934 to document and quantify the hydrologic cycle in semiarid uplands with intermittent headwater streams. New and innovative equipment was necessary to measure rainfall and streamflow in this mountainous terrain. Long-term monitoring has revealed a number of hydrologic patterns following land use change and wildfire. Water quality monitoring shows that the SDEF has had very high levels of nitrate due to its proximity to the heavily polluted Los Angeles Basin. These nitrate levels, which approach federal standards, are exacerbated by land use change and fire. In the future, evaluating the hydrologic response from climate change models and testing specific climate change predictions for southern California may be possible using the 80-year record of temperature, rainfall, and streamflow from the San Dimas Experimental Forest.

INTRODUCTION

The San Dimas Experimental Forest (SDEF) is a nearly 7000 ha research preserve administered by the USDA Forest Service, Pacific Southwest Research Station, and has been the site of extensive hydrologic monitoring for over 80 years (Dunn and others 1988). Established in 1934, the original mission of the SDEF was to quantify the water cycle in semiarid upland terrain and to determine if any extra water could be harvested to support agriculture and domestic water supply in the valleys below (Robinson 1980). With its headquarters at Tanbark Flat (34º 12' N latitude, 117º 46' W longitude), the SDEF is located in the San Gabriel Mountains, about 45 km northeast of Los Angeles, California (fig. 1).

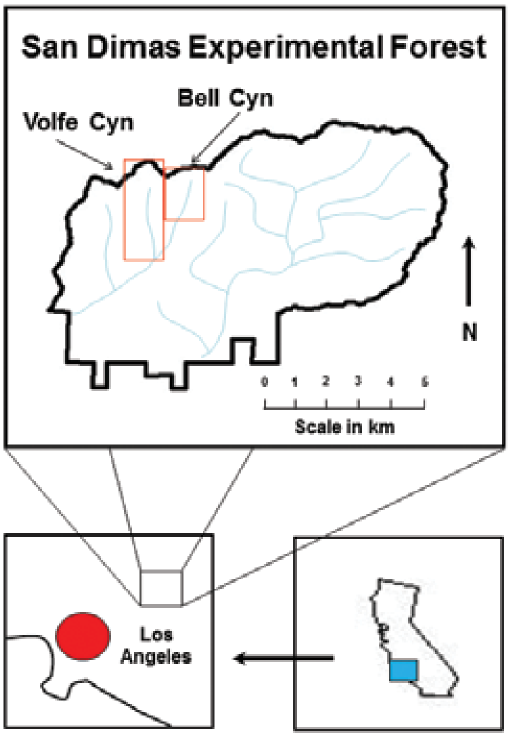

Figure 1—Location map of the San Dimas Experimental Forest.

The Experimental Forest and Range network can be considered a cornerstone of USDA Forest Service Research due primarily to the long-term datasets acquired from these reserves. Long-term observations and monitoring can document subtle ecological shifts that are harbingers of environmental change not readily apparent from studies of only a few years duration. Furthermore, the effects of complex environmental processes or the response to land use changes or to management manipulations can only be fully appreciated over time.

In the early 1930s, the hydrologic cycle was fairly well understood in the humid eastern section of the United

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States where water was abundant. However, in the arid and semiarid West, water was scarce and watershed management was in its infant stages (Leopold and others 1964). Headwater streams were intermittent and rainfall-runoff relationships were virtually unknown. Long periods of drought were punctuated by large floods which destroyed property while millions of cubic meters of potentially usable water escaped to the sea. Because of the general scarcity and variability in water supply, wise watershed management depended on a better understanding of the water cycle in semiarid uplands. This prompted the establishment of the SDEF.

STUDY AREA

Elevations in the SDEF study area range from 450 to 1675 m and topography consists of a highly dissected mountain block with steep hillside slopes and steep channel gradients. Bedrock geology is dominated by Precambrian metamorphics and Mesozoic granitics that produce shallow, azonal, coarse-textured soils (Dunn and others 1988). The region experiences a Mediterranean-type climate, characterized by hot, dry summers and cool, wet winters. Temperatures range from -8^{o} C to 40^{o} C. Mean annual precipitation, falling almost exclusively as rain, is 715 mm in the SDEF (80-year record), but rain during individual years can range from 252 to 1848 mm.

Native vegetation in the SDEF consists primarily of mixed chaparral, a dense shrubland of drought-tolerant plants 3-5 m in height. Plant cover on south-facing slopes ranges from closed stands of chamise (*Adenostoma fasciculatum*) and ceanothus (*Ceanothus* spp.) to more open stands of chamise and black sage (*Salvia mellifera*). North-facing hillsides are dominated by scrub oak (*Quercus berberidifolia*) and ceanothus, with occasional hardwood trees – coast live oak (*Quercus agrifolia*) and California laurel (*Umbellularia californica*) – occurring on moister shaded slopes and along the riparian corridors (Wohlgemuth 2006). Some pine-oak forest occurs in the higher elevations, especially on north-facing aspects, including canyon live oak (*Quercus chrysolepis*), big-cone Douglas-fir (*Pseudotsuga macrocarpa*), sugar pine (*Pinus lambertiana*), and a remnant grove of ponderosa pine (*Pinus ponderosa*).

Fire has been a part of the southern California landscape since before recorded history and is the disturbance event which drives much of the local environmental response (Sugihara and Barbour 2006). Fire alters the physical and chemical properties of the soil – bulk density and water repellency – promoting overland flow on the hillsides at the expense of infiltration (DeBano 1981). This water is quickly conveyed to the adjacent stream channels and flooding is a common post-fire hydrologic response (Krammes and Rice 1963). Stand-replacing wildfires occurred on the SDEF in 1919, 1960, and 2002.

One of the management treatments following the wildfire in 1960 was the type-conversion of the native chaparral vegetation in some watersheds to a mixture of perennial grasses. It was thought that type-conversion would aid in future fire control and would enhance water yield by replacing deep-rooted shrubs with shallow-rooted grasses (Rice and others 1965). These perennials included a variety of wheatgrass species (*Agropyron* spp.), Harding grass (*Phalaris tuberosa* var. *stenoptera*), big bluegrass (*Poa ampla*), smilo grass (*Piptatherum miliaceum*), and Blando brome (*Bromus hordaceous*) (Corbett and Green 1965). Over time, many of the seeded grass species have disappeared from the sites and substantial amounts of buckwheat (*Eriogonum fasciculatum*) and black sage have established on the type-converted watersheds.

METHODS

The hydrologic monitoring for this study was conducted in Volfe and Bell Canyons (fig. 1). Volfe Canyon watershed is 300 ha in size and covered with native chaparral vegetation. Volfe Canyon is a long-term reference watershed managed for minimal human disturbance. Bell Canyon consists of multiple headwater basins ranging in size from 25 to 40 ha. Originally covered with native chaparral vegetation, Bell2 was type-converted to perennial grasses in 1958 and Bell1 was similarly converted in 1960 (Dunn and others 1988). Bell3 remains in chaparral.

Rainfall on the SDEF has been measured continuously since 1934 in a network of weighing raingages (Dunn and others 1988). Total annual rain for individual study areas was computed as the area-weighted average of the nearest stations measured in millimeters. Rainfall was assumed to be spatially uniform across the catchments and was also calculated as cubic meters based on watershed area.

Streamflow has been measured in Volfe and Bell Canyons since 1938 (Dunn and others 1988). Stream discharge was measured in weirs for low flows (<50 L/s) and flumes for high flows. Stage heights were read from float-driven stream charts at 6 hour intervals and at inflection points during storm events. Discharge was computed from stage height using rating curves developed for each instrument and summed over the time intervals to get an annual water yield in cubic meters.

Water quality has been measured in Volfe and Bell Canyons since 1986. Pumping samplers draw aliquots of stream water every 6 hours while the creeks are flowing. Samples are analyzed in the laboratory using an ion chromatograph with detection limits of 0.01 ppm. Nitrate (NO_3) is the primary analyte.

RESULTS AND DISCUSSION

Equipment Development

During the 1930s and 1940s, much time and effort were spent developing equipment to measure the various hydrologic components at SDEF. On mountainous terrain, a more accurate measurement of rainfall was realized if the gage was tilted perpendicular to the hillside slope rather than set in a vertical orientation (Hamilton 1954). Streamflow was intermittent, flashy, and often heavily bulked with sediment. Several tiers of weirs and flumes were necessary to accurately measure the range of expected discharges from the larger watersheds: a 90° weir in the throat of a 0.91 m (three-foot) flume nested in a 2.44 m (eight-foot) flume. Moreover, a supercritical flume was developed – the San Dimas flume – capable of measuring flows containing considerable sediment and debris (Wilm and others 1938). A large lysimeter complex was built to quantify soil moisture, percolation, and evapotranspiration (Patric 1961), although this apparatus suffered from significant design flaws and was subsequently abandoned.

Fire Response

Post-fire flooding has long been documented in southern California (Kraebel 1934). Using the rainfall and runoff records from SDEF, this post-burn hydrologic response can be quantified and compared to pre-fire values. Storm rainfall, peak flows, and resulting flow volumes for Volfe Canyon watershed are shown in table 1. Prior to the 1960 wildfire, the response to these early season moderate rainfall events is modest. However, the first four storms following the wildfire shows a spectacular contrast. Both peak flows and flow volumes increase by four orders of magnitude compared to pre-fire levels from similar storms (table 1). From these before and after hydrologic findings from the SDEF, the downstream damage to human communities by flooding following a wildfire in southern California can be easily explained.

Type-Conversion

Runoff records from the multiple small watersheds in Bell Canyon were used to assess the effects of type-conversion. None of the immediate post-fire years (1961-1964) were used in this analysis, eliminating the fire effects mentioned above. A test of normalcy using the Bell3 control watershed indicates a different runoff response trajectory between the pre- and post-conversion time periods (fig. 2). To account for this response difference, the runoff ratios (RO), the percentage of rainfall that leaves the watershed as streamflow (Ratzlaff 1994), were calculated and the type-converted catchments were compared to the control. Bell1 watershed, which produced more runoff than Bell3 even prior to the vegetation change, increased its water yield by a factor of three following type-conversion (fig. 3). Bell2 had a similar response (fig. 4). Thus, type-conversion does appear to increase runoff and water yield from southern California chaparral watersheds. However, apart from the wholesale ecosystem changes and effects on native fauna, subsequent studies have shown that there are serious environmental consequences of type conversion, including increased erosion in the form of soil slips and slope failures (Rice and others 1969) and degraded water quality (Riggan and others 1985).

Table 1—Rainfall, peak flows, and flow volumes from the Volfe Canyon watershed for similar storms before and after a wildfire of July 1960.

Storm Dates	Rainfall	Peak flow	Flow volume
	mm	L/s	m^3
Dec. 3-4, 1955	34.3	0.157	14
Oct. 19-21, 1958	27.4	0.116	2
Nov. 2-5, 1958	41.4	0.300	1
Jan. 11-12, 1960	36.1	0.068	2
Wildfire – July 1960			
Oct. 9-10, 1960	21.3	3351	37,455
Nov. 3, 1960	36.8	370	48,060
Nov. 5-6, 1960	39.6	5538	55,258
Nov. 12, 1960	32.5	9347	412,037

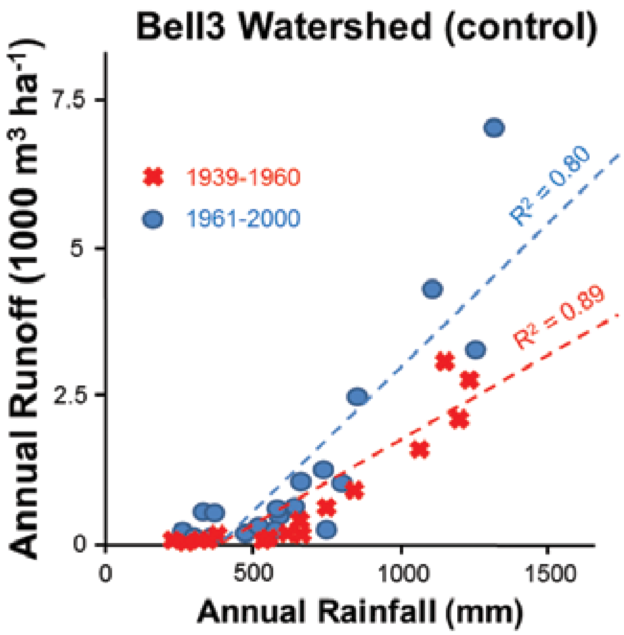

Figure 2—Rainfall-runoff relationships in Bell3 watershed during the pre- and post-type-conversion time periods of Bell1 and Bell2 watersheds. The immediate post-fire years of 1961-1964 have been omitted from this analysis.

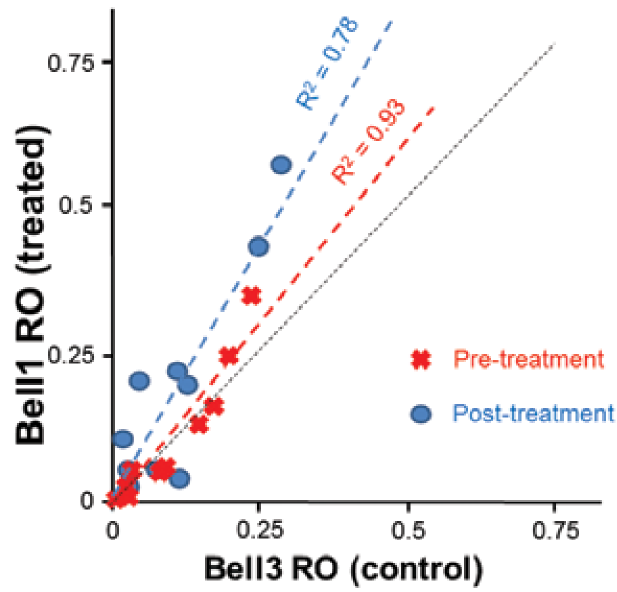

Figure 3—Runoff ratios (RO), the percentage of rainfall that leaves the watershed as streamflow, from Bell1 pre- and post-conversion compared with RO from Bell3. Black dotted line is the line of one-to-one correspondence.

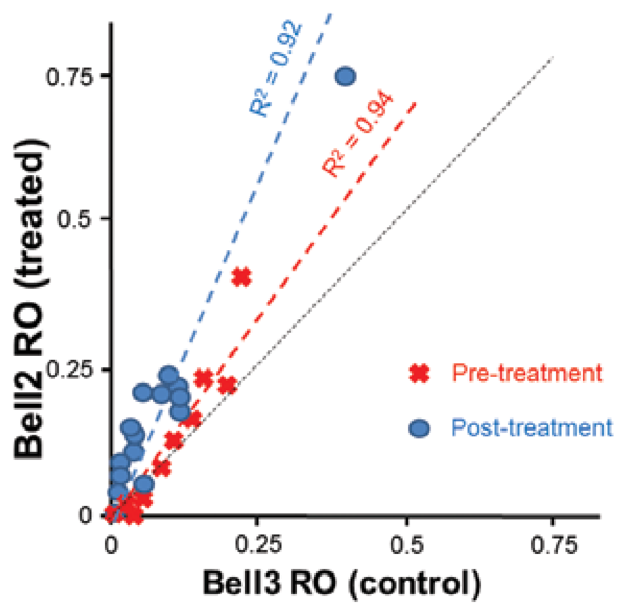

Figure 4—Runoff ratios (RO), the percentage of rainfall that leaves the watershed as streamflow, from Bell2 pre- and post-conversion compared with RO from Bell3. Black dotted line is the line of one-to-one correspondence.

Water Quality

Water quality sampling began sporadically in the early 1980s and became a programmatic feature of SDEF monitoring in 1986. High rates of atmospheric N deposition are produced in southern California by chronic air pollution, primarily from automobile exhaust from the Los Angeles Basin. These pollutants become trapped in an inversion layer that gets pushed up against the inland mountains by daily onshore air flows from the Pacific Ocean. This deposition in the headwater mountains, including the SDEF, has led to measured surface water levels of nitrate that approach the Federal EPA standard of 10.0 mg L^{-1} for nitrate-N (Fenn and others 2003). Substantial amounts of nitrate are washed off shrub surfaces during the summer and autumn, when small storms are interspersed with pollution episodes. Measured stream water nitrate concentrations in the SDEF have been as high as 7.0 mg of nitrate-N L^{-1} in undisturbed native vegetation. These values are some of the highest measured rates in the United States and up to 1000 times greater than more pristine areas in southern California (Riggan and others 1985). Although there has been a slight decline in N deposition over the last twenty years with more stringent pollution control requirements, nitrate levels in SDEF stream water remain high (Meixner and others 2006). Fire can further increase nitrate levels in SDEF stream water. Initial data following a prescribed fire showed that nitrate-N concentrations in streams could be as much as 15.7 mg L^{-1}, 1.5 times the Federal standard (Riggan and others 1985). Greater concentrations and yields of nitrate were also measured in watersheds that were type-converted to grasslands. Possibly, the greater nitrate levels reflected greater subsurface soil exposure caused by the landsliding in these altered landscapes coupled with the more rapid water flux through the shallow-rooted grasses. Maximum measured yield was 19.4 Kg of N $ha^{-1}yr^{-1}$ in grass vegetation compared to 10.0 Kg N $ha^{-1}yr^{-1}$ in chaparral (Riggan and others 1985).

INTO THE FUTURE

If the model projections are correct, climate change will profoundly affect global weather patterns. Although there is considerable variability among the many models, the general consensus is that temperatures will increase and precipitation will decrease in most continental areas (Cayan et al. 2008). This will alter the local hydrologic cycle (the disposition of rain and snow, evaporation, transpiration, the timing of snowmelt, water storage) that will in turn affect water supplies. In southern California, the Mediterranean pattern of wet winters and dry summers is projected to continue. However, some models predict that the area could experience periods of up to 30 years where annual rainfall is more than 10 percent below historical levels (Cayan et al. 2008), and the annual precipitation could decrease by 20 to 40 percent by the year 2100 (EPA 2013). One possible benefit of the long-term weather, rainfall, and stream runoff records at SDEF may be the ability to estimate the hydrologic response to expected climate change. Because of the natural variability inherent in any long-term dataset (e.g. figure 2), surrogates for climate change scenarios may already exist in the SDEF archives. Thus, realistic estimates of hydrologic response could be used for planning purposes as well as to validate the output of climate change models.

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