

Hydrology of Mediterranean-Type Ecosystems: A Summary and Synthesis¹

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Presentations in two sessions have addressed three major hydrologic problems of Mediterranean-type ecosystems: flooding and sedimentation, water yield, and water quality. Because fire is common to all Mediterranean-type ecosystems and profoundly affects their hydrologic systems, its effect on each of these problems was also addressed. This summary highlights the important points discussed, identifies some obvious gaps in our understanding, and suggests some major research and management needs.

FLOODS, EROSION, AND SEDIMENTATION

Every speaker dealt with the problem of flooding and sedimentation, and in three-fourths of the presentations it was the main topic. It is undoubtedly the major hydrologic concern in California's chaparral, and although less important in other Mediterranean areas, it is nevertheless recognized as significant.

An obvious reason for the problem is the Mediterranean climate itself. Howard (these Proceedings) has pointed out that erosion rates tend to increase with both the seasonality of rainfall and the tendency toward relatively large, infrequent storms, two key characteristics of a Mediterranean climate. Further, depending on temperature, highest erosion rates occur in those regions having between 300 and 750 mm of annual rainfall (Schumm 1977), and this is true for most of the stations in the world's Mediterranean areas (McCutchan 1977). In parts of California and Chile, the size and intensity of storms are increased by the presence of high mountains near the ocean.

It is interesting that Brock and DeBano (these Proceedings) did not find a significant increase in erosion rates with increases in slope. Other

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studies³ (Anderson and Trobitz 1949) similarly found no strong correlations between slope and sediment production. Superficially, these results may seem to contradict common sense, but the concept of thresholds and equilibrium helps to explain it. Because erosion in arid regions tends to be episodic, not continuous (Schumm 1977; Howard, these Proceedings), slopes tend to reflect a state of equilibrium with their environment, and erosion occurs only after some type of disturbance (storm, fire, earthquake, etc.). This equilibrium is maintained over a range of conditions, and the limits of these conditions are thresholds. When a disturbance causes one or more thresholds to be exceeded, the slope erodes in order to establish a new equilibrium.

Carson and Kirkby (1972) have used the term "angle of maximum slope" to describe a common threshold. Essentially, it is the maximum angle at which the soil on a slope can resist failure under gravity. It is based on concepts of soil mechanics, and in its strictest sense can only be applied to slopes of uniform, unconsolidated material. As a concept, however, it clarifies the effect of thresholds on very steep slopes. As a slope approaches this angle (threshold), it becomes more and more unstable until its stability depends almost entirely on a specific set of local conditions (such as root biomass or moisture). Its angle of maximum slope, in the strict sense, is actually exceeded. The term, "oversteepened," is often used to describe this metastable condition. When a disturbance occurs, large increases in erosion are necessary to achieve a new equilibrium, and the result is an episode of high sediment production. Rice (1974) has proposed that a fundamental change in the dominant erosion processes occurs as slopes become steeper, and mass-wasting replaces fluvial processes. He further suggests that this threshold is somewhere around 50 to 60 percent, which tends to agree with my observations. In California's San Gabriel Mountains, where oversteepening is common, large erosion episodes are also common, and the extremely high rates of sediment yield reported by Bruington (these Proceedings) should be considered quite normal.

In a recently completed study, Taylor (1981 and these Proceedings) has identified six major inland sedimentation processes in coastal southern California. Rainsplash and channel transport are ubiquitous processes which dominate in the absence of the other four. Creep, landsliding, dry ravel, and sediment flows reflect local conditions and are relatively site specific. Dry ravel and landslides are characteristic of oversteepened

³Pers. commun., Brent D. Taylor, Environmental Quality Laboratory, California Institute of Technology, Pasadena, Calif., 1978.

environments and tend to dominate in southern California's mountains and offshore islands. Rice (1974) estimates that these two processes account for over 85 percent of the erosion in southern California's chaparral zone. Brumbaugh and others (these Proceedings) report high incidence of soil slippage and landsliding on heavily overgrazed Santa Cruz Island. Sediment flows are also common, and their occurrence is often related to fire (Wells 1981).

Anderson and others (1959) have pointed out the yearly dry-wet cycle of erosion in California. Channels fill during the dry season, mainly by dry ravel, then scour in the wet season when the rains produce channel flow. Krammes (1965) found that channel filling actually occurs throughout the year. This fill-scour sequence, operating in cycles longer than 1 year, could be important in determining the amount of sediment produced by large flood events with return periods of several years. Vanoni and others, and Wells⁴ have suggested that the low rates of sediment production by the storms of 1980 in southern California were caused by a lack of sediment supply in stream channels, a result of intense channel scour by similar storms in 1978. With only 2 years between these major storm events, there was not sufficient time for a large supply of sediment to accumulate in the channels. A longer time between such events would allow more sediment to be delivered from the hill slopes to the channel, and thus more would be available for transport when the next event occurred.

Fire

Fire is common to all Mediterranean ecosystems and probably figures more prominently in their management strategies than any other single factor. This is certainly true of its effect on flooding and sediment yield. The so-called fire-flood sequence (U.S. Dep. Agric., Forest Serv. 1954) is well documented in California's chaparral, and has been observed in other Mediterranean ecosystems as well. Brown (1972) and Burgess and others (1981) have described its occurrence in Australia, and Van Wyk (these

⁴Vanoni, V. A.; Born, R. H.; Nouri, H. M. Erosion and deposition at a sand and gravel mining operation in San Juan Creek, Orange County, California. Paper presented at symposium on storms, floods and debris flows in southern California and Arizona 1978 and 1980. Committee on Natural Disasters, National Research Council. September 17-18, 1980, Pasadena, California.

Wells, W. G. II. The storms of 1978 and 1980 and their effect on sediment movement in the eastern San Gabriel front. Paper presented at symposium on storms, floods and debris flows in southern California and Arizona 1978 and 1980. Committee on Natural Disasters, National Research Council. September 17-18, 1980, Pasadena, California.

Proceedings) reported an increase of suspended sediments in runoff water for 10 months after prescribed burning of South Africa's fynbos.

The effect of fire on flooding and sediment production in California is dramatic. Rowe and others (1954) have estimated that sediment yields in the first year after fire can be as much as 35 times normal. Peak flows can be four times normal for a 1-year event, and 34 times normal for an event with a 0.1-year return period. Wells (1981) reported that the sediment yield from 0.008-ha plots on a 50 percent slope in California chaparral increased by over two orders of magnitude in the first year after burning. Boyle (these Proceedings) presented a dramatic case study in which a series of postfire flows caused a residential development to be converted into a floodway.

The immediate cause of these extremely high flows is order-of-magnitude increases in both sediment bulking ratios and total runoff. Normal rates of postfire overland flow are 10 to 15 times the prefire rates, and increases of as much as 40 times the prefire rates have been measured (Rice 1974). Davis (1977) reported that sediment bulking ratios in the San Gabriel Mountains increase from 40 to 60 times in the first year after fire. In unburned catchments, sediment makes up from 1 to 2.5 percent of the total flow, and, for a given basin, these values remain quite constant for all discharges. After fire, sediment makes up from 30 to 60 percent of the total flow. Indeed, many postfire flood events are sediment flows rather than water. When the increases in runoff are combined algebraically with the increase in bulking ratio, the results are very near those values reported by Rowe and others (1954).

The underlying reasons for these increases in runoff and bulking ratio are not fully understood and are the subject of many current studies. The most obvious fire effect is removal of vegetation and litter from an area; removal of litter has been shown to increase sediment production (Brock and DeBano, these Proceedings). This removal exposes the soil surface to the undiminished impact of falling raindrops, which has been shown to be the major source of energy for "sheet" erosion during storms (Mutchler and Young 1975). Young and Wiersma (1973) found that raindrop energy accounted for over 90 percent of all the movement of sediment into rills from interrill areas and for about 10 percent of the total sediment transport off a site. Dunn and others (these Proceedings) have found that a unique postfire community of heat-shock fungi imparts some ability to recently burned soils to resist detachment by raindrop impact. The full range of this fungal-soil interaction is currently under study.

Two other important postfire erosion processes are dry ravel and rill formation. Dry ravel has been shown to increase substantially after fire (Krammes 1960), and changes induced in the particle-size distribution of soils by heating in a fire may play a part in this increase (Duriscoe and Wells, these Proceedings). After the first

winter storms, the most striking erosional features on freshly burned slopes are the numerous rills. There is considerable qualitative evidence to suggest that water-repellent soil and extensive rill formation on burned slopes are closely linked (Wells 1981), and fire in chaparral is known to produce a layer of water-repellent soil a few centimeters beneath the soil surface (DeBano 1981).

The fire effect does not last long. Rowe and others (1954) estimated that whole basins return to normal in 8 to 10 years. Brown (1972) found that 4 to 5 years was sufficient for recovery in Australia. Plot studies indicated that hill slopes in California chaparral recover in 3 years (Wells 1981). Van Wyk (these Proceedings) reported that only 10 months are required in South Africa's fynbos.

Management Implications

The cost of sediment management can be very high even without the effect of fires. Bruington (these Proceedings) reported that sediment control on one reservoir in the San Gabriel Mountains has cost almost \$1/2 million per year for 45 years. The costs of postfire flooding in Harrison Canyon (Boyle, these Proceedings) are equally impressive. In land use planning, we must fully understand the magnitude of the forces we are dealing with and the time periods over which they operate. Only then will we be successful in managing their effects.

WATER YIELD

Another problem shared by most Mediterranean areas is a relative scarcity of water. Most of the drainages in these areas are ephemeral washes, and there are few perennial streams. The ever-increasing demands for water are forcing us to look for ways to increase usable runoff in these areas. Franklin (these Proceedings) has reported that this is one of the major land management goals of the State of California.

The two major approaches to increasing water yield in the western United States have been vegetation manipulation (usually type conversion) and periodic prescribed burning. Water harvesting--the use of prepared catchments to collect rainfall--is quite common in Australia and Israel but has found limited use in the United States except in parts of Hawaii (Myers 1975). Hibbert and others (these Proceedings) have looked into both vegetation manipulation and prescribed fire as ways to increase runoff in Arizona chaparral. Their results seem to indicate that the response to vegetation manipulation is better than that to prescribed burning.

Attempts to increase water yield have been made in southern California, and increases have been noted after both fire and type conversion (Colman 1953, Crouse 1961). However, accelerated erosion

in the wake of these efforts has been a major problem (Orme and Bailey 1970, Rice 1974), and the costs frequently outweigh the benefits. One of the problems with using fire is the increase in bulking ratios found by Davis (1977). It is difficult to recover usable water from flows which are 30 to 60 percent sediment, and disposal of the sediment is also a problem.

It must be expected that any attempt to increase water yield will probably incur a cost in terms of increased sediment yield. The relative magnitude of this cost will diminish, however, as the demand for water continues to grow. It seems certain, therefore, that ways to minimize this trade-off will be an important subject for future hydrologic research. Increased water production is already a major management goal.

WATER QUALITY

Water quality received the least attention of the three major problems addressed in this session. Perhaps this is related to the problem of water scarcity. When water is scarce, we don't worry as much about its quality. As we are able to increase water yield and as our management becomes more intensive, water quality must receive more attention. Only three aspects of water quality will be discussed here: nutrients in streams, suspended sediments (turbidity), and thermal pollution. Problems such as industrial pollution, and the effects of road construction and fire control, are too complex to be adequately addressed. Again, fire has important effects.

Thermal pollution changes the rates of both chemical and biological activity in natural streams, and thus influences the chemical makeup of the water delivered. It also has a direct effect on the streams' suitability as a fish habitat. Streamside vegetation is an important component of most Mediterranean ecosystems and is extremely important in maintaining stream temperature. Any degradation of such vegetation by fire, recreational use of the area, or clearing results in much higher mean temperatures with large diurnal fluctuations. Heating by fire itself does not seem to have a significant effect (Norris and others 1978).

Elevated levels of nutrients in runoff water following fire have been reported, but none are so high that they actually become pollution problems. Tiedemann and others (1979) reported that several workers in the United States have found increases in $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, and organic-N, as well as in major cations (Ca, Mg, Na, and K). Van Wyk (these Proceedings) found major increases in Na and Cl and minor changes in SO_4 and HCO_3 after fire in the fynbos of South Africa. Riggan and Lopez⁵

⁵Riggan, P. R.; Lopez, E. L. Nitrogen cycling in the chaparral ecosystem. Paper presented at Western Society of Naturalists meeting; December 27-29, 1979, Pomona, California.

reported elevated NO₃-N levels in runoff from chaparral sites that have been converted to grass. They also found high NO₃-N levels in storm runoff (relative to base flow levels) in the San Gabriel Mountains. Dry deposition from the smog of nearby Los Angeles⁶ and NO₃-N in rainfall (Liljestrand and Morgan 1978) may account for part of this.

Suspended sediment is often the most significant type of pollution. Increases in suspended sediment following fire have been reported from Australia as well as the United States (Brown 1972, Tiedemann and others 1979). Turbidity is not just a fire effect; almost any disturbance to the ecosystem can result in turbidity in nearby streams. Anderson and others (1976) reported eightfold increases from logging operations in northern California. Because cations are adsorbed by suspended clay particles, turbidity can be an important factor in nutrient loss.

HYDROLOGIC MODELING

As our knowledge of the environment advances, the need for a systems approach to it becomes more apparent, leading to the use of models that can rapidly generate information needed for informed management decisions. Two models have been discussed in these sessions. Anderson and Phillips (these Proceedings) presented a method for using existing data to evaluate the effects of fire on different hydrologic parameters. Rice and others (these Proceedings) presented a model which predicts changes in hill slope stability under different fuel management strategies. The former is designed primarily to assist managers, while the latter has both research and management applications.

Modeling, though an important tool in our discipline, must be carefully used. Many hydrologic models outstrip the data base in sophistication, so that highly refined models are often used to process very crude data. As a result, the answers reflect the model rather than the data. The real need in hydrology is for more data suitable for use in the models.

CONCLUSIONS

The Mediterranean-type regions of the world are attractive places to live and will continue to grow in population, with accompanying growth in the need for more intensive land management. This need, in turn, demands that we understand the natural processes operating on these lands better than we ever have before. These discussions suggest that some of the more pressing needs are these:

- A better understanding of fire's effects on sedimentation and flooding. We do not yet understand the fire-flood sequence well enough to deal effectively with its associated problems. High postfire erosion rates result from a major change in the erosion processes operating on a watershed. This change causes all sedimentation processes to reflect both the frequency and intensity of fires.

- A more detailed study of steepland erosion processes, particularly mass-wasting. Methods for dealing with erosion on agricultural lands have often proved inadequate in mountainous terrain. If we understand steepland erosion processes, we can deal with them more realistically.

- A quantitative assessment of delivery of sediment to channels, storage of sediment in channels, and transport of sediment through channels. A series of sediment budget studies covering different environmental conditions (postfire, fuelbreaks, undisturbed, etc.) is needed.

- A greater effort to increase water yield without incurring unacceptable penalties in sedimentation and pollution. Combinations of techniques designed for specific sites should produce the best results.

- More studies of nutrient loss from disturbed watersheds and the process by which it occurs. Also needed are studies of the chemistry of natural streams and the degree of variability in their chemical makeup.

- A stronger and more widespread effort to collect baseline data to support efforts in hydrologic modeling. This requires the establishment and maintenance of more data collection sites, particularly for sedimentation data.

For my final comment, I must mention the potential of prescribed fire in sediment management. Fire affects almost every part of the ecosystem, and its selective application can produce many benefits. Its use as a possible means of increasing water yield has already been mentioned, and it shows real promise as a preemptive tool for reducing the potential size of wildfires. It may also be useful, in a similar way, as a sediment management tool. Erosion in mountainous terrain cannot be stopped--nor should it be. Its consequences, flooding and sediment production, have to be managed. The long-term sediment yield rates in the San Gabriel Mountains are 10 to 20 tonnes/hectare (5 to 10 tons/acre) annually. An estimated 70 percent of all sediment production in California's chaparral is triggered by fire (Rice 1974); the fire-flood sequence has already been mentioned. Burning catchments, periodically, in small patches produces a mosaic of different-aged vegetation, lessening the chance that a major fire will burn an entire catchment at one time. Channels can usually contain the postfire flows from these smaller prescribed burns, and the mosaic, by reducing the chance of burning an entire catchment, also reduces the chance of a catastrophic postfire flood.

⁶Pers. commun., h. M. Liljestrand, Department of Civil Engineering, University of Texas, Austin, Tex., 1979.

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