Chapter 7
Sediment Delivery, Flood Control, and Physical Ecosystem Services in Southern California Chaparral Landscapes

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Abstract Southern California chaparral environments, with steep mountain slopes, semi-arid climate, and non-cohesive soils, are very erosive landscapes. Wildfire is the dominant ecological disturbance event in chaparral and it greatly accelerates flooding and erosion, which are directly and/or indirectly related to the loss of the protective vegetation. Since the 1920s, dams and debris basins have been constructed by public works agencies to protect the growing population and infrastructure of southern California by intercepting and impounding flows of water and debris. Dams also capture stream runoff for supplying water to downstream agriculture and urban populations. Major sediment inflows into dams and debris basins following fire can reduce capacity and threaten the ability to provide flood control and water supply. Chaparral provides physical ecosystem services that aid in flood hazard reduction, sediment retention, and the supply of water as well as protecting habitat for endangered species and soil quality.

Keywords Chaparral · Erosional processes · Flood control · Physical ecosystem services · Sediment delivery · Stormwater conservation

7.1 Introduction

Chaparral vegetation covers the foothills and lower mountain hillslopes over an extensive area of southern California (see Fig. 1.1). The physical characteristics of geology, topography, and soils in this region produce very erosive landscapes, a

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E. C. Underwood et al. (eds.), *Valuing Chaparral*, Springer Series on Environmental Management, https://doi.org/10.1007/978-3-319-68303-4_7

condition that is further exacerbated by repeated wildfire that is occurring increasingly more frequently. The potential hazards fostered by this wildfire disturbance, such as flooding and accelerated sediment fluxes, threaten downstream human communities, prompting public works agencies to build flood control, sediment retention, and stormwater conservation networks that are expensive to construct and maintain. Intact native chaparral landscapes offer watershed protection by naturally reducing floods and retaining sediment. Other physical ecosystem services in chaparral environments also include water supply, protection of threatened and endangered species and their habitats, and protection of soil quality.

7.1.1 Sediment Fluxes in Southern California Chaparral

Sediment flux is the movement of granular rock and organic material through a watershed from hillslopes, through stream and river systems, and ultimately to the ocean. Southern California has some of the highest erosion rates, and hence sediment fluxes, in the world—comparable to the Himalayas or the Andes (Jansson 1988). The current landscape reflects the removal of soil and sediment from the uplands and deposition of this material in the adjacent lowlands over the last several millennia. Local erosion depends on many factors including topography, geology, soils, vegetation cover, and rainfall patterns.

Southern California is a zone of active tectonics associated with crustal plate interactions along the San Andreas Fault system, resulting in mountain-building in the Coast Ranges, the Peninsular Ranges, and the Transverse Ranges. Studies have shown that local mountain chains are uplifting at rates as high as 7.6 mm per year, despite the high erosion rates (Scott and Williams 1978; Spotila et al. 2002). This ongoing tectonic uplift has produced steep topography and exposed fractured, highly erodible crystalline basement rocks at the earth's surface. In chaparral environments, this erosive rock material, combined with any overlying soft sedimentary strata, weather to thin, coarse-textured, azonal soils (Dunn et al. 1988). These soils are typically non-cohesive, meaning that they lack clays and organic glues that bind the individual soil granules together. Southern California is classified as a Mediterranean-type climate region, consisting of cool, wet winters followed by long summer droughts. This amount and pattern of precipitation combined with the shrubland vegetation cover in the region maximize erosion (Langbein and Schumm 1958). Chaparral vegetation is drought tolerant, due in part to its small, sclerophyllous leaves (see Chap. 1). However, the waxy, resinous substances that allow chaparral to endure the long, dry summers also render it very prone to wildfire (Rice 1974).

Wildfire has a profound effect on sediment fluxes in chaparral. Fire has been a part of the southern California landscape since before recorded history and is the disturbance event which drives many of the environmental responses in chaparral ecosystems (Sugihara and Barbour 2006). Fire is also responsible for much of the erosion experienced across the landscape. With the combustion of the vegetation canopy and the surface litter layer, along with fire-induced changes in soil properties, erosion on hillslopes greatly increases (Wohlgemuth et al. 2009). Hillslope hydrology is also affected, increasing water delivery to the stream channels that may increase streamflow magnitude and initiate a range of sediment flux responses, including debris flows or slurries of mud, which can threaten both local flora and fauna as well as downstream human communities. Natural fire recurrence in chaparral ecosystems is 50–100 years (Minnich 1989), but fire frequency has increased significantly over the last century related to the large numbers of anthropogenic ignitions (Safford 2007).

Postfire natural hazards to human endeavors have been recognized in southern California since the late 1800s (Munns 1919; Wohlgemuth et al. 2009). Flooding and accelerated erosion from burned areas can threaten life, property, and community infrastructure at the wildland-urban interface. Residents and campers have been killed by flash floods and debris torrents, in many cases at significant distances downstream from the location of the fire. Homes and businesses have been inundated with debris originating from adjacent or nearby burns. Roads, bridges, utility lines, pipelines, and communication lines have all been damaged by both flood and mud. To mitigate these foregoing hazards, flood control and protection from transported sediment has been the goal of public works agencies in southern California since at least the 1920s (Wohlgemuth et al. 2009).

7.1.2 Flood Control and Stormwater Conservation in Chaparral

Southern California has historically been subjected to large but infrequent flooding events that occasionally shifted the flow paths of the region's rivers and streams. Southern California has also been subjected to long drought periods in between the large flooding events. Not only does this lead to a higher probability of wildfire but also an increase in postfire flooding when storms return.

The flood control and stormwater conservation history in Los Angeles County is representative of southern California as a whole. For example, a devastating storm hit the Los Angeles region in February 1914, causing widespread flooding, erosion damage, and deposition of over three million cubic meters of silt in the ports of Los Angeles and Long Beach. More than 50 people died and there was over $10 million worth of damage (approximately $237 million in 2015 dollars). In the aftermath of the flood, the State Legislature, responding to requests for action from Los Angeles County leaders, created the Los Angeles County Flood Control District in June 1915, the first flood control district in the State of California. The District was given the dual mission:

"…to provide for the control and conservation of the flood, storm and other waste waters of said district, and to conserve such waters for the beneficial and useful purposes by spreading, storing, retaining or causing to percolate into the soil within said district, or to save or conserve in any manner, all or any of such waters, and to protect from damage from such flood or stormwaters, the harbors, waterways, public highways, and property in said district" (Los Angeles County Flood Control Act, Section 2 of 1915).

Table 7.1 Southern California Flood Control Districts and dates of establishment

Agency	Established
Los Angeles Flood Control District	1915
Orange County Flood Control District	1927
San Bernardino County Flood Control District	1939
Ventura County Flood Control District	1944
Riverside County Flood Control and Water Conservation District	1945
Santa Barbara County Flood Control and Water Conservation District	1955
San Diego County Flood Control District	1966

Eventually, other areas in southern California followed suit as their populations, agricultural development, and urban development expanded, and major storms affected their populations and assets (Table 7.1).

Meanwhile, as far back as the 1890s the federal government recognized that stands of intact vegetation have a stabilizing effect on streamflow. This tends to prevent erosion and siltation, thereby maintaining the navigability of streams and water supply for power, irrigation, and urban use, and reducing devastating floods. It was also recognized that loss of vegetation from fires, logging, and mining activities had significant adverse impacts on this stabilizing effect. Legislation was passed to establish forest reserves, with the specific direction to make:

"provisions for the protection [of forest reservations] against destruction by fire and depredations..." (Organic Administration Act of 1897).

Among the earliest forest reserves was the San Gabriel Timberland Reserve (subsequently the Angeles National Forest), which was set aside primarily for the protection of irrigation projects and municipal water supplies (see Chap. 15).

The newly formed Los Angeles County Flood Control District started work in the 1920s, building several dams in the mountains (that would eventually total 90 across the county), serving a dual flood control and stormwater capture function, and building flood control channels in the valleys and coastal plains below. In subsequent plans, the District laid out the basis for a future water conservation system, pioneering the establishment of large scale artificial groundwater recharge facilities (spreading grounds) at locations adjacent to the major flood control channels. The intention of these spreading grounds, consisting of shallow basins with sand and gravel bottoms, was to enable diverted stormwater to percolate into the underlying groundwater aquifers, thereby providing a reliable source of water that could be pumped for agricultural, residential, and industrial use. The District partnered with both the US Army Corps of Engineers on flood control construction and the US Department of Agriculture Forest Service for upstream mountain erosion control to reduce the movement of eroded material in and below the Angeles National Forest. This had the dual purpose of protecting water supplies and also reducing flood risk to downstream development.

With the formation of flood control districts in southern California came the philosophy for flood control and water conservation, again illustrated by the actions of the Los Angeles County Flood Control District. Officials in southern California recognized early on the need to conserve water flowing from the mountains to the floodplains. As such, major flood control dams were also built with water conservation in mind. Additional water conservation was to be accomplished by in-stream percolation through the earth-bottom channels where feasible. In subsequent years, more sophisticated water conservation methods were developed after infrastructure was completed to deal with the worst flood threats. For example, the Los Angeles County plan of flood control consisted of several elements:

- The construction of major dams in the mountainous upper reaches of the main drainage systems to contain peak stormwater discharge and to regulate downstream flows. By reducing peak flows at the headwaters of major drainage systems, the downstream channels could be designed for lower flow rates.
- The straightening and stabilization of major natural river channels throughout the entire coastal plain to facilitate rapid drainage. The philosophy was to reduce flood damage by directing stormflows away from urban areas and to the ocean as quickly as possible.
- The development of standards for the design of flood control infrastructure to ensure an adequate level of regional flood protection. Eventually the District based its design standards on the major storms that occurred in 1938 and 1943. In short, its major infrastructure calls for safely handling the runoff from a once in 50-year storm event (a probability based on rainfall intensity) falling on a previously burned watershed that has 4 years of postfire vegetation recovery, the soil of which has been saturated by 3 days of antecedent storms (Los Angeles County 2006).
- The decision was made to leave many of the channels with “soft” bottoms (natural un-armored channel beds) which allowed for the flood waters, and water released from the dams to percolate through into the underlying groundwater aquifers.
- The development of dedicated, off-channel spreading grounds to allow stormwater that would otherwise flow to the ocean to be diverted for increased percolation into groundwater aquifers. The aim was to increase water supply for a growing population.

As southern California agencies began developing and operating their flood control and water conservation infrastructure, it became abundantly clear that impacts from not only stormwater but also sediment—particularly that which was associated with “fire-flood sequences”—needed to be addressed. Originally, small check dams were constructed in mountain areas to control erosion and debris flows downstream of burned areas (Eaton 1932). However, debris basins—retention structures at canyon mouths dedicated to capturing debris flows and sediment before they reach foothill communities—were soon recognized also to be critical for dealing with the effects of postfire flooding in the region (Los Angeles County 1931).

It took a large scale fire in 1933 and subsequent debris flows on New Year’s Day 1934 in the foothill communities of Altadena, La Canada Flintridge, La Crescenta, and Tujunga in Los Angeles County to provide the impetus for the construction of debris basins. In La Crescenta alone, the debris flow, which occurred in little over 1 h, destroyed previously installed check dams, deposited over 450,000 m^3 of debris, claimed 40 lives, and destroyed 400 structures. The estimated cost of the damages was \$6 million (approximately \$106 million in 2015 dollars). During the mid-1930s, the District constructed its first debris basins with the intention of providing a more permanent solution to protect downstream communities.

7.2 Sediment Delivery in Chaparral

Sediment delivery is the transfer of soil and rock material from one component of the landscape to another: from the hillslopes to the stream channels and along the stream networks to a watershed outlet (i.e., a higher order stream channel, a lake, or the sea). On chaparral covered hillslopes, sediment is delivered by both hydrologic and gravity-driven erosion processes. At a larger scale, in headwater channels and larger streams, both classic fluvial transport and debris flows are responsible for sediment transfer. Fire enhances these delivery processes and continues to affect sediment movement for years into the future.

7.2.1 Hillslope Delivery Processes

Hillslopes are the source of nearly all the sediment moving through any landscape. Sediment generated on the hillslopes by the weathering of rock material is transported downhill by the various agents of erosion (wind, water, and gravity) and accumulates in the riparian zone at the base of the hill. In southern California these mechanisms of transport are amplified in the steep topography caused by active tectonics, while the forces of resistance are minimized by the non-cohesive soils that are typically dry. Hillslope sediment transport can be classified into two types: (1) surface erosion, either by dry ravel or water-borne processes, and (2) mass erosion, dominated by landslides.

7.2.1.1 Surface Erosion

The first type of surface erosion, dry ravel, refers to the dry, unconsolidated movement of granular material down a hillslope solely under the influence of gravity (Rice 1974). Dry ravel always requires a trigger mechanism, but these may be subtle, such as animal movement across a hillslope, microearthquakes, wind whipping the low-lying branches of shrubs onto the ground surface, or even differential thermal expansion of soil granules on a hot summer day. Ravel is a ubiquitous process, especially on steeper slopes (Gabet 2003b), but is often overlooked or unappreciated. However, studies have shown that dry season surface erosion can equal or exceed hydrologically dominated wet season surface erosion in some chaparral landscapes (Anderson et al. 1959). Dry ravel can be a primary mechanism for delivering hillslope sediment to headwater channels (Florsheim et al. 2015).

The second type of surface erosion consists of water-borne processes on hillslopes, including rainsplash and overland flow. Raindrops can dislodge and transport loose soil grains and preferentially transport them downhill. As rain persists, water accumulates on the ground surface, where much is absorbed by the organic material, with the litter layer acting a huge sponge. The remainder will infiltrate into the soil mantle, eventually percolating to the groundwater table. However, if the rain is falling faster than the soil infiltration rate, or if the ground becomes fully saturated, the excess moves across the ground surface as overland flow. Initially, this flow is as a thin film of sheetwash, but the differential resistances on the hillslope organize this runoff into distinct microchannels or rills. However, overland flow is very rare on unburned chaparral hillslopes with a canopy and litter cover, consequently water only reaches the stream channels by relatively slow flow paths through the soil mantle (Rice 1982).

7.2.1.2 Mass Erosion

Mass movement events—such as landslides, the failure of whole hillsides—can produce tremendous devastation. However, large landslides are relatively rare events and are almost always associated with heavy rain lubricating zones of geological weakness, such as slip planes in sedimentary rock, secondary dikes and sills in crystalline rock, or at the boundary between very different rock formations (Selby 1993). More common are small landslides or shallow “soil slips” produced by high intensity or persistent rain, where the weight of the extra water overcomes the balance of forces including the root strength provided by the vegetation (Rice et al. 1969; Campbell 1975). Debris flows (often called “mud flows”) are a mass movement process that may be initiated as water mixes with landslide debris during high intensity rainfall events. Debris flows may originate on hillslopes and extend into steep headwater channels that have slopes greater than about 20 degrees (Prancevic et al. 2014). While mass erosion from large landslides, multiple soil slips, or debris flows may be spectacular, surface erosion by dry ravel is more pervasive. Both contribute to the sediment delivery from chaparral hillslopes.

7.2.2 Watershed Delivery Processes

Once soil and sediment material is delivered from the hillslopes to the channel networks, stream transport processes rout it through the riparian zone and eventually to a watershed outlet. In perennial streams, this transport is accomplished more or less continuously by the traditional fluvial processes described below. In ephemeral or intermittent streams—those that flow only in certain years or at certain times of the year—the same fluvial processes apply but transport is episodic, allowing hillslope material to accumulate in the channels between runoff and erosion events. In the chaparral environments of southern California, periods of low to moderate streamflow are punctuated irregularly by large storms that flush loose sediment out of the riparian networks, and the cycle of channel filling by hillslope delivery begins anew.

7.2.2.1 Fluvial Transport and Storage

The movement of sediment by rivers and streams is governed by the size of the streambed material, the channel gradient, and the volume of streamflow or discharge. Particles are entrained when shear stresses overcome the resistances of mass and inertia, with larger particles requiring more force for entrainment and subsequent transport than smaller ones (Leopold et al. 1964). Once entrained, sediment is transported by the force of the moving water. Some of the substances in transport can be chemically dissolved by the water and are then carried as solute load or in solution. Very fine particles (silts and clays) are transported as suspended sediment within the water column. Heavier sands are bounced along the streambed and heavier gravels and cobbles slide or roll as bedload. If stream power decreases because of increased resistances, a reduction in slope, or a drop in discharge, particles will begin to settle back to the bed and banks. The material will remain in temporary storage until the forces increase, and entrainment and transportation commences again. Thus sediment delivery in rivers and streams is usually episodic, especially for the larger particles.

The primary source of sediment that is entrained and transported by rivers and streams is from the alluvium stored in the channel bed and banks, originally delivered from the hillslopes. The transport of this material can result in bed and bank scour (unless the stream channel is carved into bedrock) which occurs along preferential flow paths where velocity is maximized. The streambed can be vertically downcut or incised, while the stream banks can be horizontally or laterally eroded.

7.2.2.2 Debris-Laden Flows

In contrast to the routine sediment transport of sediment along a stream channel, hyper-concentrated flows and debris flows are special forms of fluvial transport that occur when there is an excessive supply of sediment delivered to the stream channels, such as after a landslide. Sediment transport processes in hyper-concentrated flows are similar to water flows described above, whereby the force of the fluid mobilizes and transports sediment grains until the flow recedes, leaving channels filled with sediment that is easily entrained by later stormflows (Florsheim et al. 1991).

Debris flows are a type of mass movement that are usually confined to steep headwater stream channels. Although they can be generated when the debris from a landslide event reaches a creek or stream, debris flows may also form by the process of bulking, where more and more sediment is added to the mix such that the behavioral properties of the flow are no longer fluid. The resulting mixture in a debris flow often includes organic debris and has the consistency of wet concrete. Debris flows, though relatively rare, have tremendous erosive power in steep channels and can scour substantial sections within the riparian zone, transporting particles the size of small boulders long distances down the stream channel (Cannon and Gartner 2005).

7.2.3 Fire Effects on Sediment Delivery

Fire radically changes the rates of sediment delivery in chaparral ecosystems. With combustion of the vegetation and the litter layer, raindrop interception greatly decreases and water cannot be absorbed into the now-absent organic surface material. Moreover, fire causes physical and chemical changes in the soil. Organic particles are consumed in the uppermost soil layer, leaving voids that can collapse to increase the soil bulk density. Partial combustion of chaparral duff and the re-deposition of the vaporized waxy substances from the leaves into the cooler soil below can create a hydrophobic or water-repellent layer that blocks or greatly reduces infiltration (DeBano 1981). These changes reduce the resistances to sediment transport on hillslopes thereby enhancing the agents of erosion that govern both dry season and wet season sediment delivery from hillslopes to channels in chaparral environments. In the stream channel itself, fire can consume large organic debris, removing these stable components that may affect habitat and geomorphology. However, most of the alterations in postfire stream channel and watershed response derive from the massive changes on the hillslopes that deliver extra water and sediment from the hillslopes to the riparian networks.

7.2.3.1 Processes

Dry ravel transport rates greatly increase in postfire chaparral. Ravel can actually begin while the fire is still burning as organic barriers on the ground surface are consumed, liberating the soil and sediment trapped behind vegetation that dammed this material on the hillslopes. Immediately after a fire, ravel is pervasive on steep slopes, as the hyper-sensitive ground surface will initiate a cascade of soil material with the slightest disturbance. Ravel may continue for days or weeks after a fire until loose sediment on the burned hillslope is stabilized. Wind or other disturbances can re-initiate ravel transport.

Water-borne erosion processes on hillslopes are also magnified following a fire. With the removal of the vegetation canopy and litter layer, the mineral soil is subjected to unimpeded raindrop impacts, vastly improving splash efficacy. In addition, the spongy litter is lost, thereby reducing the water-holding capacity of the soil mantle and producing water repellent soil material a few centimeters below the surface, effectively eliminating infiltration and percolation. Consequently, water moves across the ground surface as overland flow which, on unprotected soil, forms rills that scour sediment off the hillslopes. Moreover, once the rill networks are created, subsequent rainfall is quickly conveyed off the hillslopes along these rills to the stream channels below (Wells 1981).

Contrary to popular notions, landsliding and soil slips are not enhanced in chaparral environments by fire. Rather, with the loss of infiltration and the increase in overland flow, less water is available to percolate to zones of geologic weakness that would initiate mass movement events. However, saturation of the upper soil layer resulting from the production of a water repellent layer can generate thin debris flows on the hillslopes that can greatly increase sediment delivery (Gabet 2003a).

Fluvial transport, bed and bank scour, and sediment storage in streams are all affected by fire. Reduced infiltration on the hillslopes promotes more overland flow and consequently greater runoff in the stream channels (Loaiciga et al. 2001). The initial sediment response of most stream channels in postfire chaparral is to fill with sediment from adjacent slopes, first by dry ravel and then by overland flow. Once the easily mobilized sediment is removed from the hillslopes, subsequent storms produce mostly water that tends to scour the newly formed channel deposits (Florsheim et al. 1991). Postfire channel sedimentation will preferentially fill stream pools, smoothing both the longitudinal and transverse river profiles (Keller et al. 1997).

Compared to unburned watersheds, debris flows are far more common in the postfire chaparral environment. Formed by the extra water generated on the hillslopes mobilizing the stored sediment in the stream channels, postfire debris flows scour the headwaters (further bulking the flows with sediment) then deposit the rocks and mud in large lobes where the channel gradient sufficiently flattens, often creating temporary barriers or dams (Wells 1987). However, despite their impressive ability to deliver sediment, debris flows following fire are still relatively rare events. Postfire sediment transport and channel flushing are more likely to occur by normal fluvial or hyper-concentrated flow processes than by high-magnitude but infrequent debris flows (Keller et al. 1997).

7.2.3.2 Fire Recovery

Accelerated postfire sediment delivery on chaparral hillslopes will eventually attenuate to prefire background levels as the area recovers. Postburn vegetation re-growth in chaparral ecosystems is very rapid, and sprouting from root crowns can occur within weeks of the fire. The initial herbaceous canopy can shield the ground surface and help stabilize hillslope sediments (Barro and Conard 1991). However, the decline in erosion also results from the depletion of the easily mobilized surface sediment in the first year postfire and the subsequent exposure of less erodible material from deeper in the soil column (Wohlgemuth 2006). Sediment delivery from chaparral hillslopes can recover to preburn rates in as little as two years (Wohlgemuth et al. 1998; Wohlgemuth 2015), although there are examples of somewhat longer recovery periods (Krammes 1965).

As with hillslopes, sediment yields at the broader watershed scale are greatest immediately after a fire, then decline to preburn rates as the catchments recover. Time to recovery depends on specific site factors, the severity of the fire, and rainfall patterns. As noted above, sediment delivery from the hillslopes can return to normal in just a few years. However, given the episodic nature of channel transport associated with flow fluctuations and the capacity for internal temporary sediment storage, watershed sediment yields may remain elevated for longer time periods. Based on vegetation re-growth and channel morphology, Davis et al. (1989) determined that burned watersheds initially recovered to prefire conditions after about 5 years, while Rowe et al. (1954) estimated postfire watershed recovery to be 8–10 years.

7.3 Flood Control and Water Supply Infrastructure

Flood control and water conservation infrastructure has evolved over the years. This is a result of structural improvements and more accurate weather forecasting, combined with the ability for real-time monitoring of rainfall rates, reservoir conditions, and channel flow rates. Historically, flood control and reducing the risk of flood damage to downstream communities has always held precedence over water conservation operations in southern California. However, increased population, more frequent droughts, and reduced availability of imported water have increased the focus on enhancing infrastructure and operations to increase capture of local stormwater runoff. These activities help ensure a more sustainable local water supply. New technologies make it possible to optimize stormwater runoff to capture it for local and regional water storage. For example, by using telemetry systems and collecting real-time weather and channel flow data, dam outflows can be limited to maximize water capture while still reducing downstream flooding. Similarly, after the storm event, dams can release water at a volume tailored to the rate of percolation in the spreading grounds. Given the ability to control water releases, dams can be filled to capacity and drained to their minimum pools more than once during a wet storm season.

7.3.1 Structures

The flood protection and water conservation systems in southern California are made up of several components. These components each perform their own unique functions to protect lives, property and infrastructure from flooding, and to contribute to their region's water supplies.

Fig. 7.1 Schematic diagram of a flood control dam describing different components (County of Los Angeles, Department of Public Works, www.lasedimentmanagement.com)

7.3.1.1 Dams

There are over 282 major dams in southern California. Dams, and the reservoirs behind them, can serve single or multiple functions including flood control, debris control, and stormwater capture for water supply. Many also provide recreational benefits within and downstream of the facilities. The majority of these dams provide flood control, but some were built specifically for water supply storage, with water pumped to them, and are not located in watercourses.

Dams can be made out of earth fill (rock and soil with a clay core) or concrete with a variety of different forms (Fig. 7.1). Flood control dams in southern California typically range from 7.5 m (24.6 ft) high to over 100 m (328.1 ft) high with reservoir capacities from approximately 62,000 m^3 (50.3 acre-ft) to as much as 65.8 million m^3 (53,345 acre-ft), although most are of the smaller size. Flood control dams are typically located in mountainous areas where narrow canyons provide suitable locations to block the watercourse of large upstream watersheds. The size of watersheds identified for dam placement can range from 500 to 45,000 ha (1236–111,197 acres).

In comparison to dams of similar heights on watersheds with gentler slopes (e.g., in northern California), southern California dams do not have huge storage capacities and a single major storm has the potential to completely fill a reservoir. As a consequence, dam operations need to constantly focus on evaluating storm conditions using advanced weather forecasting tools and real-time data. Based on this information, water is released through valves to decrease reservoir levels in antici-

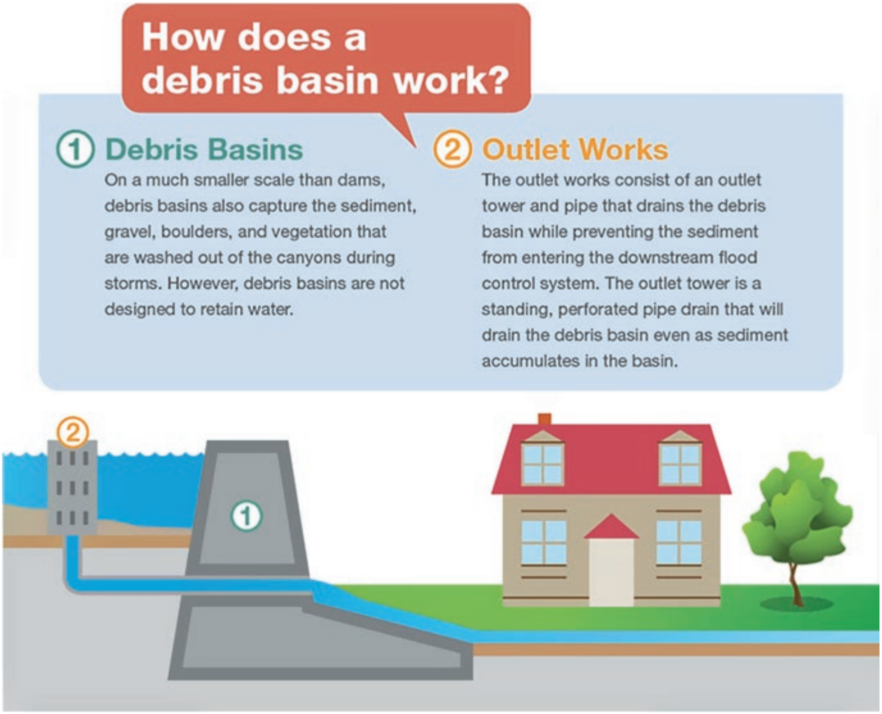

Fig. 7.2 Schematic diagram of a debris basin describing different components (County of Los Angeles, Department of Public Works, www.lasedimentmanagement.com)

pation of peak storm inflow rates. The goal is to remain in control of the dam and prevent the overflow of water through the spillway by managing the reservoir level through controlled releases. From the dams in Los Angeles County, spillway flows occur approximately only once every 7–10 years.

7.3.1.2 Debris Basins

Debris basins serve the single function of capturing sediment and debris from the upstream undeveloped watershed while allowing the stormflows to continue downstream. They are essentially small dams that typically have no valves to operate (Fig. 7.2). There are over 200 debris basins in southern California, usually 4.5–15 m (14.8–49.2 ft) high with less than 62,000 m^3 (50.3 acre-ft) of capacity but can be as large as 308,400 m^3 (250 acre-ft). Debris basins are typically formed by constructing an earthen or concrete dam near the mouth of a canyon and excavating a basin upstream to collect the debris-laden water. The heavier material such as boulders, rocks, and gravel are deposited on the bottom of the basin, while the settled, clear water flows out of the debris basin through the outlet tower and discharges to the downstream channel (Fig. 7.2).

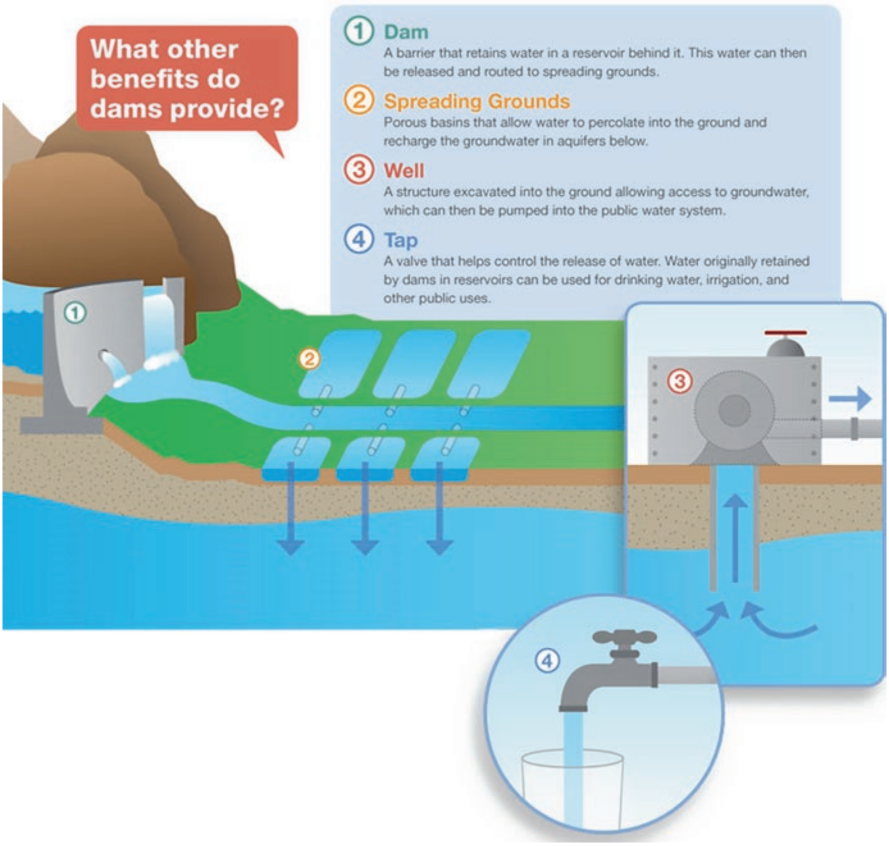

Fig. 7.3 Schematic diagram of a spreading ground describing different components (County of Los Angeles, Department of Public Works, www.lasedimentmanagement.com)

7.3.1.3 Spreading Grounds

Spreading grounds consist of one or more basins formed with earthen berms or levees where flow is directed by gates and weirs to the individual basins to percolate through layers of sands and gravels into the subsurface aquifer (Fig. 7.3). This recharges the groundwater basin which can later be pumped for water supply. In Los Angeles County, the largest spreading ground covers 93 ha (230 acres) of land and includes over 20 basins. It should be noted that many of these facilities not only recharge the groundwater basins with local storm runoff and stormwater captured by the dams, but also with imported water purchased by the local water entities for the purpose of groundwater replenishment. In addition, starting in the 1960s, they are also recharged with recycled water supplied by local wastewater treatment facilities. In Los Angeles County, the Flood Control District began constructing spreading grounds in the 1920s and now operates 27 such facilities which collectively recharge on average more than 370,000 m^3 (300 acre-ft) per year of water to the underlying aquifers.

7.3.2 Sediment Impacts on Flood Control Structures

Southern California experiences fire-flood cycles, where fires periodically burn mountainous areas and torrential rains result in debris flows pouring out of the mountains, which either inundate flatlands or are captured in flood control or water conservation infrastructure. As sediment accumulates behind dams and debris basins, the capacity of these facilities is diminished and outlet works are blocked. This compromises their ability to reduce flood risks and provide stormwater capture for water supply, as well as physically disrupting the functioning of the facility. As a consequence, stormflows cannot be attenuated and released to match downstream channel capacities and stormwater can fill the reservoir until uncontrolled spillway flows occur at much higher flow rates. In addition, blocked outlet works render the reservoir unable to be drained which is extremely important in the unlikely event of a dam safety emergency. Finally, it should be noted that sediment is heavier than water and in some cases would produce unacceptable forces on a dam or debris basin during a seismic event.

Blocked or partially blocked outlet works similarly preclude the ability to release captured stormwater for recharge to downstream spreading grounds, thereby reducing local water supply. Moreover, the increased turbidity of the released sediment-laden water may prevent distributing the water at spreading grounds due to concerns of plugging the sands and gravels with fine material and reducing percolation. Also, to slow the sediment accumulation near the outlet works, a "buffer pool" is created at the upper end of the reservoir to encourage sedimentation. This pool further reduces capacity for capturing stormwater for the regional water supply. Maintaining capacity through sediment management and sediment removal projects is therefore paramount to the sustained operations of these facilities.

7.3.3 Required Maintenance and Sediment Removal Projects

Debris removal from dams and debris basins is critical to ensure flood or debris protection for homes and infrastructure downstream of the facility and to maximize stormwater capture. The debris volume that accumulates in reservoirs in the mountains and along the foothills of southern California is tremendous. In 2012 it was estimated that it may be necessary to remove as much as 49 million m^3 (39,725 acre-ft) of sediment from these facilities over the next 20 years (for comparison, the Rose Bowl in Pasadena would hold about 300,000 m^3 (243 acre-ft) (LACDPW Sediment Management Plan, March 2013 [http://dpw.lacounty.gov/lacfcd/sediment/stplan.aspx]). The amount of material removed from a debris basin can range from 750 to 225,000 m^3 (0.6–182.4 acre-ft) and can take from 2 days to several months depending on their size and how quickly the sediment can dry so that it can be handled and transported.

7.3.3.1 Dams

Large dams in California are regulated by the California Department of Water Resources' Division of Safety of Dams (DSOD). DSOD requires regular monitoring and reporting on the structural and functional integrity of the dams and, when necessary, rehabilitation of dams to meet strict state and federal seismic, spillway capacity, and emergency dewatering standards. In addition, in areas with significant debris flow issues, like Los Angeles County, maintenance includes the costly periodic removal of accumulated debris from the reservoir.

Removal of sediment can be in the form of sluicing (i.e., washing the sediment out of the reservoir to the streams below), dry excavation, or dredging (i.e., excavation in standing water). Sluicing, which historically was performed outside of southern California's storm season, has the lowest cost, but has fallen out of favor due to concerns about impacts to downstream habitat and water quality. However, sluicing in the storm season is now being considered due to the desire to restore the natural balance of sediment in the habitats of major streams and slow down the rate of debris accumulation. In contrast, dry excavation requires substantial or complete draining of the reservoir, and transporting the material by conveyor belt, trucks, or combination thereof to a disposal site. Finally, dredging lessens the amount of reservoir draining, but also requires large dewatering areas for the wet sediment/water slurry to dry in addition to a final disposal site, which can be many kilometers away from the reservoir.

Needless to say, all these techniques for sediment removal from dams are very expensive. For example, in Los Angeles County, during the last 25 years, dry excavation has been the preferred clean-out method at the reservoirs. The excavation of 250,000 m^3 of sediment from Santa Anita Reservoir in 2011/2012 and transport via conveyor belt to a disposal site 3 km (1.9 miles) away cost $7.5 million (almost $30 per cubic meter [0.0008 acre-ft]). Similarly, the proposed removal of 1.8 million m^3 (1459.3 acre-ft) of sediment from Devils Gate Reservoir and associated truck transport to nearby landfills is estimated to cost $65 million (about $36 per cubic meter).

7.3.3.2 Debris Basins

Maintenance of these facilities consists of regular monitoring of the debris dam's condition, annual mowing (vegetation removal) of the basin/inlet bottom, and periodic clean-outs of the sediment. Several of the larger debris dams are under the regulatory jurisdiction of the State's DSOD and thus have more monitoring and reporting requirements than the smaller ones. Debris basin/inlet bottoms are mowed to ensure debris flows enter the basin and debris settles in a manner that maximizes the capacity of the basin. Mowing also facilitates clean-out of the structures and reduces the organic content of the debris being removed, thus making it easier and less expensive to find places for disposal. According to the Los Angeles County Sediment Management Strategic Plan, the cost of non-emergency debris basin clean-outs can be about $9.37 per cubic meter and as much as $80 per cubic meter during emergencies. Factors that influence these costs include the need to work 24-h shifts to restore capacity as soon as possible, handling material multiple times (if it is too wet and cannot be transported on roads, it can require stockpiling and drying and/or mixing with other material), and the distance to the placement site. Following the historic 2009 Station Fire, the 2009–2010 storm season delivered 933,280 m^3 (757 acre-ft) of sediment into 30 Los Angeles County debris basins. The cost to remove the sediment was $24,159,000 ($24.60 per cubic meter).

7.3.3.3 Spreading Grounds

Maintenance of the spreading grounds consists of keeping the intake clear, keeping the diversion works in the channel and the inter-basin gates in good working order, removing sediment and opportunistic vegetation from the settling basin and spreading basins, and scarifying the basin bottoms to re-open up the top layer of the soil on the basin bottoms.

Without removal of sediment from upstream dams and debris basins, more material (typically finer grain sizes) is washed downstream. This increases the likelihood of sediment moving into the percolation basins beyond the settling basins and further increasing the maintenance needs at the spreading grounds. In areas where burned watersheds do not drain into dams, the storm runoff delivered to downstream spreading grounds is more turbid. Even after heavier sediment drops out of the flows when they exit the canyons or debris basins, finer material can still make its way through the valleys below. Stormflows can be so silt-laden that the operators of spreading grounds find it necessary to divert flows so they do not enter the spreading grounds in order to prevent clogging of the spreading basin bottoms.

7.3.3.4 Sediment Placement Sites

The disposal of sediment removed from reservoirs and debris basins has always been challenging. The haul distances from facilities to landfills can be very long (over 30 km or 18.6 miles), and costs can also be very expensive (over $11 per cubic meter). As far back as the 1950s, the public works agencies explored the feasibility of having local gravel quarries utilize the sediment from the reservoirs and thus reduce the disposal costs. Although some of the sediment had been found to be of suitable commercial quality, the reservoirs' remote mountain locations were beyond the haul distances that quarry operators consider to be economically viable. As a result, the flood control districts acquired their own hillslope properties or obtained Special Use permits from the US Forest Service for properties in the mountains to serve as sediment placement sites. These sites serve as storage facilities for sediment from reservoirs and debris basins. However, the sediment placement sites are of finite capacity, and finding new sediment placement site locations is difficult. In 2013 Los Angeles County completed a Sediment Management Strategic Plan to explore alternatives which can reduce the environmental and social impacts of sediment management. The plan identified utilizing a mix of local gravel quarries, many of which are now nearly mined out, and landfills needing a daily cover of sediment to seal the waste. The plan would also use the existing sediment placement sites to accommodate occasions when sensitive resources are involved, the quarries are unable to economically process the sediment, or only small amounts are required for covering landfills.

7.4 Physical Ecosystem Services in Chaparral

Chaparral environments provide several physical ecosystem services, most of which are not appreciated until the vegetation is removed. Intact stands of chaparral reduce floods, retain sediment, provide clean water through the infiltration and replenishment of aquifers, protect threatened and endangered species and their habitats, and protect soil quality. These services are temporarily eliminated if the chaparral is removed, as after a large wildfire. However, these services could be permanently impaired if the chaparral is significantly degraded by persistent drought associated with climate change, by alterations in land use, or following invasion by non-native species associated with high frequency fires.

7.4.1 Flood Hazard Reduction Services

Chaparral ecosystems contribute to flood hazard reduction by reducing runoff both on the hillslopes and in the stream networks. When the vegetation canopy and litter layer are in place, overland flow on the hillslopes is rare and subsurface flow to the stream channels through the soil mantle is slow. With the removal of the canopy and the litter layer by fire, along with the attendant changes in soil properties, overland flow on the hillslopes is pervasive and delivery to the streams via the surface network of rills is rapid. Streams and rivers convey the floodwaters generated by large storms to the watershed outlet. In unburned chaparral catchments substantial flood events only occur about once a decade and only after the largest storms. Following a fire, large flood events are commonplace and can occur even after moderate rains (Rowe et al. 1954).

Increased floods in chaparral environments after fire are well documented. In watersheds with extensive prefire stream records in southern California, fire increased flow volumes by 3 to 5 times compared to an adjacent unburned catchment (Sinclair and Hamilton 1955). Using burned and unburned soil infiltrometer tests and a calibrated watershed model, Nasseri (1988) showed that moderate storms could produce floods of considerable magnitude in a burned chaparral watershed. Comparing similar storms both before and after a fire in chaparral, Krammes and Rice (1963) documented postfire peak flows that were 200–800 times greater than unburned levels.

The consequences of postfire flooding in chaparral depend on the downstream values at risk. In natural landscapes, postfire flooding can scour the channel bed and banks, re-arrange the position of boulders and large logs, and remove streamside vegetation. This can alter the geomorphology of the riparian zone and the habitat of the flora and fauna that occupy this niche. However, at the wildland-urban interface, the hazards of postfire flooding and the potential damage to human endeavors can be extensive.

One approach for estimating the value of chaparral for flood hazard reduction can be roughly calculated as the likelihood that assets would be impacted based on the difference in prefire and postfire threshold storm recurrence intervals. Assuming that flooding from a 10-year storm immediately following a fire would cause the same damage to property and infrastructure as a 50-year storm in unburned vegetation and assuming a five year recovery period after a fire described by an exponential decay curve (Rowe et al. 1954), the values at risk would be 7.5 times more likely to be affected by flooding after a fire than if the watershed had not burned. This increased likelihood of postfire flooding with the removal of chaparral vegetation is the impetus for the dams built and maintained by various flood control districts to protect life, property and public infrastructure in downstream human communities.

7.4.2 Sediment Retention Services

Chaparral environments retain sediment by reducing the surface erosion on the hillslopes and by reducing scour and transport in the stream channels. While some erosion is inevitable for granular material on an inclined surface, this transport is minimized under intact chaparral. If the vegetation is removed, the extra water and sediment generated on the bare hillslopes is quickly delivered to the streams which scours the bed and banks, increases transport capacity, and perhaps produces debris flows by mobilizing the loose sediment stored in the channels.

Increased postfire sediment yield in chaparral is also well documented, although rates can vary considerably depending on topography, soils, fire severity, and precipitation patterns. Rowe et al. (1954) determined that burned chaparral catchments produced an average of 35 times more sediment than those same watersheds prior to fire, similar to rates reported by Wohlgemuth (2015). Pase and Ingebo (1965) found that postfire sediment yields in chaparral can be 100 times greater than those from nearby unburned watersheds. In an extreme case, Kraebel (1934) documented burned catchments that experienced 1000 times more sediment yield than comparable unburned watersheds.

The consequences of postfire sediment yield in chaparral also depend on the downstream values at risk. In natural landscapes, postfire sediment transport in streams can incise the upstream sections of the channels and deposit this material further downstream. This incision or filling will modify the geomorphology and the habitat along the streams (Keller et al. 1997). However, at the wildland-urban interface, the risk of postfire sedimentation and the potential damage to the human built environment can be tremendous (Campbell 1975).

One method for estimating the value of chaparral for sediment retention can be roughly calculated as the likelihood that assets would be impacted based on the difference in prefire and postfire threshold sediment pulse recurrence intervals. Because sediment load is not just a function of storm size but also of sediment availability, a larger prefire storm size is necessary to compare to postfire sediment transport. Assuming that the sediment delivered from a 10-year storm immediately following a fire would cause the same damage as a 100-year storm in unburned vegetation and assuming a five year fire recovery period described by an exponential decay curve (Rowe et al. 1954), the values at risk would be 18 times more likely to be affected by sediment after a fire than if the watershed had not burned. This huge increase in vulnerability to postfire sedimentation with the loss of chaparral vegetation is the rationale for the construction and maintenance of dams and debris basins by the various public works agencies to protect downstream values at risk.

7.4.3 Water Supply Services

Chaparral ecosystems supply clean water from the outlets of larger watersheds for agricultural, domestic, and industrial uses. Rain falling on unburned chaparral gets absorbed into the litter layer, infiltrates into the soil mantle, and percolates through the fractured substrate to the groundwater table. During this slow flowing through subsurface pathways, the water is filtered of all but the tiniest soil grains and most of the contaminants derived from organic decay, unusual geology, or atmospheric deposition. Excess water not used by the hillslope shrubs or the riparian vegetation, or necessary for downstream resources, is then available for human use. As we have seen, fire increases the quantity of water delivered from the hillslopes, contributing to flooding in lower stream sections. However, fire also modifies the character of the water itself, affecting the turbidity and water chemistry, to the detriment of the anticipated water supply. After a fire, water from the hillslopes now reaches the streams primarily over the ground surface, bypassing the subsurface filtering. Thus, postfire streamflow is often laden with ash and fine sediments. Moreover, nutrients and soluble compounds from the ash are also flushed or leached from hillslope sources to become part of the water column. Therefore, although more water is generated from postfire environments, most of this water is unusable without expensive filtration. Settling in spreading grounds is not an option because those facilities will become clogged with the ash and fine sediments.

Lost stormwater supply from burned watersheds has been measured by local public works agencies. One reservoir in Los Angeles County received more than 1.7 million m^3 (1378.2 acre-ft) of sediment after a recent fire. This reduced the ability to capture stormwater annually by 617,000 m^3 (500.2 acre-ft). A similar reservoir experienced a series of fires in its contributing area and saw its capacity reduced annually by over 2.5 million m^3 (2026.8 acre-ft) The value of the lost water from these two reservoirs alone is $1.82 million per year based on the cost to replace this stormwater by purchasing imported water from the Metropolitan Water District (2016 rate of $708 per 1200 m^3 [0.97 acre-ft] for untreated water [www.mwdh20.com/whoweare/management/finincial-information]).

7.4.4 Threatened and Endangered Species Protection Services

Chaparral ecosystems are comprised of many species of flora and fauna, a number of which are considered to be threatened with extinction or extirpation (see Chaps. 2 and 3). Most of these species occupy the riparian zone but some reside on the hillslopes. All species in chaparral have adapted to a dynamic environment of extremes of heat and cold as well as flood and drought. Moreover, wildfire within the range of natural frequency is the disturbance event to which chaparral environments are adjusted. However, fire and the postfire hydrologic and sediment response pose an additional problem for threatened and endangered species at the wildland-urban interface. In the past, if postfire flooding and accelerated erosion eliminated a particular organism from a local creek, the area could be re-colonized from nearby unburned refugia. But if human development has fragmented the habitat and removed the corridors of connectivity, the threatened and endangered species could be permanently removed.

Intact chaparral reduces erosion, thereby protecting species both on the hillslopes and in the stream channels. When these services are interrupted, such as after a fire, hillslope erosion (either by dry ravel or overland flow) can remove small plants and strip away the seedbank. In the streams, aquatic organisms are subject to increased turbidity (affecting light transmission) and potentially detrimental changes in water chemistry. In addition, when the stream gradient flattens or the resistances increase, sediment load settles on the streambed or in pools, smothering any biota.

The value of chaparral to species protection is difficult to assess, but the costs of species recovery plans, monitoring, and breeding programs can be significant. Moreover, the consequences of reduced protection to threatened and endangered species when these services are not provided is the loss of individual species, altered food webs, and changes in overall species composition.

7.4.5 Soil Quality Protection Services

Chaparral cover reduces erosion, thus protecting the quality of the soil resource. Soils form as weathered rock material combines with decaying organic matter, often developing layers or horizons over time. However, soil material in mountainous southern California landscapes dominated by chaparral forms quickly but is transported rapidly by the agents of erosion. As a result, soil material lacks distinct horizons because of the low residence times on steep hillslopes. Chaparral soils are typically shallow with low fertility. Fire can liberate nutrients bound up in the organic litter cover, producing ash and char on the ground surface that can increase soil fertility. However, much of this material is removed by dry ravel and overland flow, and the residual soil is impoverished in nutrients compared to the unburned condition. With the stripping of the organic-rich topsoil, material of lower fertility is exposed at the soil surface.

The loss of chaparral by land use change also reduces soil protection. In the past, some areas of chaparral have been intentionally type-converted to grasslands to improve water yield or to expand grazing opportunities. However, with the loss of the root strength provided by chaparral shrubs, the grassy areas are susceptible to shallow soil slips (Rice et al. 1969; De Graff 1979), especially in high rainfall years. These small mass movements on formerly stable hillslopes contribute directly to immediate hillslope sediment delivery, while the scars on the hillslopes continue to be a source of soil erosion into the future.

In short, the consequences of diminished protection of the soil resource in post-fire chaparral environments is the loss of organic matter and lower soil productivity. This results in reduced plant growth and less forage for associated fauna. However, quantifying the value of chaparral for the protection of soil quality is difficult.

7.5 Summary

Southern California's chaparral environments are very erosive and these high levels of background erosion are further compounded by repeated wildfire. Erosion and sedimentation are responsible for creating the natural landscape over geologic time, but these processes are hazardous to people and the built environment. This has prompted public works agencies to construct dams, debris basins, and flood control channels to protect life, property, and infrastructure from the flooding and accelerated erosion that are invariably generated from burned watersheds as a consequence of the loss of chaparral vegetation. Chaparral environments provide many physical ecosystem services, most of which are under-appreciated by modern society (see Chap. 5). However, as burgeoning population centers continue to impinge on chaparral landscapes, the awareness of chaparral will continue to grow, as will a greater recognition of the value of chaparral ecosystems.

References

Anderson, H. W., G. B. Coleman, and P. J. Zinke. 1959. Summer slides and winter scour: dry-wet erosion in southern California mountains. Technical Paper 36. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, USA.

Barro, S. C., and S. G. Conard. 1991. Fire effects on California chaparral systems: an overview. Environment International 17:135–149.

Campbell, R. H. 1975. Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California. Professional Paper 851. US Geological Survey, Washington, D.C., USA.

Cannon, S. H., and J. E. Gartner. 2005. Wildfire-related debris flow from a hazards perspective. Pages 363–385 *in* M. Jakob, and O. Hungr, editors. Debris-flow hazards and related phenomenon. Springer Praxis Books, Berlin, Germany.

Davis, F. W., E. A Keller, A. Parikh, J. L. Florsheim. 1989. Recovery of the chaparral riparian zone after wildfire. Pages 194–203 *in* D.L. Abell. Proceedings of the California Riparian Systems Conference: Protection, Management, and Restoration for the 1990s, Davis, California, September 22–24, 1988. General Technical Report PSW-GTR-110. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, USA.

DeBano, L. F. 1981. Water repellent soils: a state-of-the-art. General Technical Report PSW-GTR-46. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, USA.

De Graff, J. V. 1979. Initiation of shallow mass movement by vegetation-type conversion. Geology 7:426–429.

Dunn, P. H., S. C. Barro, W. G. Wells II, M. A. Poth, P. M. Wohlgemuth, and C. G. Colver. 1988. The San Dimas Experimental Forest: 50 years of research. General Technical Report PSW-GTR-104. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, USA.

Eaton, E. C. 1932. San Gabriel project check dams: report to the Los Angeles County Board of Supervisors from the Los Angeles County Flood Control District. Unpublished Report.

Florsheim, J. L., A. Chin, L. S. O'Hirok, and R. Storesund. 2015. Short-term post-wildfire dry-ravel processes in a chaparral fluvial environment. Geomorphology 252:32–39.

Florsheim, J. L., E. A. Keller, and D. W. Best. 1991. Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Ventura County, southern California. Geological Society of America Bulletin 103:504–511.

Gabet, E. J. 2003a. Post-fire thin debris flows: sediment transport and numerical modelling. Earth Surface Processes and Landforms 28:1341–1348.

Gabet, E. J. 2003b. Sediment transport by dry ravel. Journal of Geophysical Research 108:1978–2012.

Jansson, M. B. 1988. A global survey of sediment yield. Geografiska Annaler 70:81–98.

Keller, E. A, D. W. Valentine, and D. R. Gibbs. 1997. Hydrological response of small watersheds following the southern California Painted Cave Fire of June 1990. Hydrological Processes 11:401–414.

Kraebel, C. J. 1934. The La Crescenta flood. American Forests 40:251–254, 286–287.

Krammes, J. S. 1965. Seasonal debris movement from steep mountainside slopes in southern California. Pages 85–89 *in* Proceedings of the Federal Interagency Sedimentation Conference, Jackson, Mississippi, January 28–February 1, 1963. Miscellaneous Publication 970, US Department of Agriculture, Agricultural Research Service, Washington, D.C., USA.

Krammes, J. S., and R. M. Rice. 1963. Effect of fire on the San Dimas Experimental Forest. Pages 31–34 *in* Proceedings of Arizona's 7th Annual Watershed Symposium, Phoenix, Arizona, September 18, 1963. Arizona Water Comission, Phoenix, Arizona, USA.

Langbein, W. B., and S. A. Schumm. 1958. Yield of sediment in relation to mean annual precipitation. Transactions of the American Geophysical Union 39:1076–1084.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman, San Francisco, California, USA.

Loaiciga, H. H., D. Pedreros, and D. Roberts. 2001. Wildfire-streamflow interactions in a chaparral watershed. Advances in Environmental Research 5:295–305.

Los Angeles County. 1931. Comprehensive Plan for Flood Control and Water Conservation—Present Conditions and Immediate Needs. Los Angeles County Flood Control District, Los Angeles, California, USA.

Los Angeles County. 2006. Hydrology Manual. Department of Public Works, Water Resources Division, Los Angeles, California, USA.

Minnich, R. A. 1989. Chaparral fire history in San Diego County and adjacent northern Baja California: an evaluation of natural fire regimes and the effects of suppression management. Pages 37–47 *in* S. C. Keeley, editor. The chaparral: paradigms reexamined. Natural History Museum of Los Angeles County, Los Angeles, California, USA.

Munns, E. N. 1919. The control of flood water in southern California. Journal of Forestry 17:423–429.

Nasseri, I. 1988. Frequency of floods from a burned chaparral watershed. Pages 68–71 *in* N. Berg, editor. Proceedings of the symposium on fire and watershed management, Sacramento, California, October 26–28, 1988. General Technical Report PSW-GTR-109. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, USA.

Pase, C. P., and P. A. Ingebo. 1965. Burned chaparral to grass: early effects on water and sediment yields from two granitic soil watersheds in Arizona. Pages 8–11 *in* Proceedings of Arizona's 9th Annual Watershed Symposium, Tempe, Arizona, September 22, 1965. Arizona Water Commission, Phoenix, Arizona, USA.

Prancevic, J. P., M. P. Lamb, and B. M Fuller. 2014. Incipient sediment motion across the river to debris-flow transition. Geology 42:191–194.

Rice, R. M. 1974. The hydrology of chaparral watersheds. Pages 27–34 *in* M. Rosenthal, editor. Proceedings of a symposium on Living with the Chaparral, Riverside, California, March 30–31, 1973. Sierra Club, San Francisco, California, USA.

Rice, R. M. 1982. Sedimentation in the chaparral: how do you handle unusual events? Pages 39–49 *in* F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanston, editors. Sediment budgets and routing in forested drainage basins. General Technical Report PNW-GTR-141. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, USA.

Rice, R. M., E. S. Corbett, and R. G. Bailey. 1969. Soil slips related to vegetation, topography, and soil in southern California. Water Resources Research 5:647–659.

Rowe, P. B., C. M. Countryman, and H. C. Storey. 1954. Hydrologic analysis used to determine effects of fire on peak discharge and erosion rates in southern California watersheds. USDA Forest Service, California Forest and Range Experiment Station, Berkeley, California, USA.

Safford, H. D. 2007. Man and fire in southern California; doing the math. Fremontia 35:25–29.

Scott, K. M., and R. P. Williams. 1978. Erosion and sediment yields in the Transverse Ranges, southern California. Professional Paper 1030, US Geological Survey, Washington, D.C., USA.

Selby, M. J. 1993. Hillslope materials and processes. Oxford University Press, Oxford, UK.

Sinclair, J. D., and E. L. Hamilton. 1955. Streamflow reactions of a fire-damaged watershed. Proceedings of the American Society of Civil Engineers, Hydraulics Division 81:1–17.

Spotila, J. A., M. A. House, A. E. Blythe, N. A. Niemi, and G. C. Bank. 2002. Controls on the erosion and geomorphic evolution of the San Bernardino and San Gabriel Mountains, southern California. Geological Society of America, Special Papers 365:205–230.

Sugihara, N. G., and M. G. Barbour. 2006. Fire and California vegetation. Pages 1–9 *in* N. G. Sugihara, J. W. van Wagtendonk, K. E. Shaffer, J. Fites-Kaufman, and A. E. Thode, editors. Fire in California's ecosystems. University of California Press, Berkeley, California, USA.

Wells, W. G., II. 1981. Some effects of brushfires on erosion processes in coastal southern California. Pages 305–342 *in* T. R. H. Davies, and A. J. Pearce, editors. Proceedings of a Symposium on Erosion and Sediment Transport in Pacific Rim Steeplands, Christchurch, New

Zealand, January 26–31, 1981. International Association of Hydrological Sciences Publication No. 132. Washington, D.C., USA.

Wells, W. G., II. 1987. The effects of fire on the generation of debris flows in southern California. Geological Society of America, Reviews in Engineering Geology 7:105–114.

Wohlgemuth, P. M. 2006. Hillslope erosion and small watershed sediment yield following a wildfire on the San Dimas Experimental Forest, southern California. Pages 41–48 *in* J. M. Bernard, J. W. Webb, and M. M. Garsjo, editors. Proceedings of the 8th Federal Interagency Sedimentation Conference, Reno, Nevada, April 2–6, 2006, Washington, D.C., USA, Interagency Advisory Committee on Water Information, Subcommittee on Sedimentation.

Wohlgemuth, P. M. 2015. Hillslope erosion and small watershed sediment yield before and after fire in southern California. Pages 977–986 *in* J. M. Bernard, M. M. Garsjo, and C. L. Hoeft, editors. Proceedings of the 3rd Joint Federal Interagency Conference (10th Federal Interagency Sedimentation Conference and 5th Federal Interagency Hydrologic Modeling Conference), Reno, Nevada, April 19–23, 2015, Washington, D.C., USA, Interagency Advisory Committee on Water Information, Subcommittee on Sedimentation.

Wohlgemuth, P. M., J. L. Beyers, C. D. Wakeman, and S. G. Conard. 1998. Effects of fire and grass seeding on soil erosion in southern California chaparral. Pages 41–51 *in* Grey, S., chair. Proceedings of the 19th Forest Vegetation Management conference, Redding, California, USA.

Wohlgemuth, P. M., J. L. Beyers, and K. R. Hubbert. 2009. Rehabilitation strategies after fire: the California, USA experience. Pages 511–535 *in* A. Cerda, and P. R. Robichaud, editors. Fire effects on soils and restoration strategies. Science Publishers, Enfield, New Jersey, USA.